Historic, archived document

Do not assume content reflects current scientific knowledge, policies, or practices.

Issued January 31, 1908.

U. S. DEPARTMENT OF AGRICULTURE,

BUREAU OF SOILS—BULLETIN No. 50.

MILTON WHITNEY, Chief.

MOISTURE CONTENT AND PHYSICAL CONDITION OF SOILS.

BY

FRANK K. CAMERON AND FRANCIS E. GALLAGHER.

WASHINGTON:

GOVERNMENT PRINTING OFFICE.

1908.

BUREAU OF SOILS.

MILTON WHITNEY, Chief of Bureau.
ALBERT G. RICE, Chief Clerk.

SCIENTIFIC STAFF.

FRANK K. CAMERON, in charge of Physical and Chemical Investigations.
FRANK D. GARDNER, in charge of Soil Management.
CLARENCE W. DORSEY, in charge of Soil Survey.
JAY A. BONSTEEL, in charge of Soil Utilization Investigations.
OSWALD SCHREINER, in charge of Fertility Investigations.
W J McGEE, in charge of Soil Erosion Investigations.

LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Soils,
Washington, D. C., September 13, 1907.

Sir: I have the honor to transmit herewith the manuscript of a technical article entitled Moisture Content and Physical Condition in Soils. In accordance with your suggestion, it has been submitted to Assistant Secretary Hays, who concurs with me in recommending it for publication.

Respectfully,

Milton Whitney,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

CONTENTS.

	Page
Introduction	7
Penetration and cohesion	10
Previous work	10
Relation of penetration to moisture content	17
Object of experiments	17
Experimental methods	18
Results for Podunk fine sandy loam	19
Results for Miami black clay loam	24
Results for Leonardtown loam	25
Results for Muck	26
Apparent specific gravity or volume	27
Previous work	27
Relation of volume to moisture content	29
Object of experiments	29
Experimental methods	30
Results for Podunk fine sandy loam	31
Results for Miami black clay loam	35
Results for Leonardtown loam	36
Results for Muck	38
Successive wetting and drying	40
Object of experiments	40
Experimental methods	40
Results for Miami black clay loam	41
Results for Muck	43
Rate of evaporation	45
Relation of rate of evaporation to moisture content	45
Experimental methods	45
Results for Podunk fine sandy loam	46
Results for Miami black clay loam	47
Results for Leonardtown loam	47
Results for Muck	48
Moisture distribution	49
Moisture films	49
Effect of moisture distribution on volume change	50
Effect of moisture distribution on penetration	51
Effect of moisture distribution on rate of evaporation	53
Critical moisture content and moisture equivalent	54
Optimum water content as regards plant growth	57
Apparatus and methods	59
Screening apparatus	59
Packing apparatus	61
Penetration apparatus	63
Apparatus for measuring volume	65
Preliminary method	65
Soil column method	67
Micrometer method	68
Cathetometer method	69

ILLUSTRATIONS.

Page.

FIG. 1. Influence of size of soil particles on penetration-moisture results for calcareous sand and for quartz, according to Puchner 14
2. Penetration-moisture results for different soil components and mixtures of them, according to Puchner 16
3. Penetration-moisture results for Podunk fine sandy loam 20
4. Penetration-moisture results for Podunk fine sandy loam by method of Puchner and by method of loose packing 22
5. Penetration-moisture results with different packings 23
6. Penetration-moisture results for Miami black clay loam 24
7. Penetration-moisture results for Leonardtown loam 25
8. Penetration-moisture and apparent-specific-gravity-moisture results for Muck 26
9. Apparent-specific-gravity-moisture results for Podunk fine sandy loam 32
10. Apparent-specific-gravity-moisture results for Podunk fine sandy loam with different packings 32
11. Volume-moisture results for Podunk fine sandy loam by the micrometer method 34
12. Volume-moisture results for Podunk fine sandy loam by the cathetometer method 34
13. Volume-moisture results for Miami black clay loam by the soil column method 35
14. Volume-moisture results for Miami black clay loam by the cathetometer method 36
15. Apparent-specific-gravity-moisture results for Miami black clay loam 36
16. Volume-moisture results for Leonardtown loam by the micrometer method 37
17. Volume-moisture results for Leonardtown loam by the soil column method 38
18. Apparent-specific-gravity-moisture results for Leonardtown loam 39
19. Volume-moisture results for Muck by the soil column method 39
20. Volume-moisture results for Muck by the cathetometer method 40
21. Volume changes with successive wetting and drying of loosely packed Miami black clay loam 42
22. Volume changes with successive wetting and drying of closely packed Muck 43
23. Rate-of-evaporation-moisture results for Podunk fine sandy loam 46
24. Rate-of-evaporation-moisture results for Miami black clay loam 46
25. Rate-of-evaporation-moisture results for Leonardtown loam 47
26. Rate-of-evaporation-moisture results for Muck 48
27. Apparatus for screening soils 60
28. Apparatus for packing soils 62
29. Penetration-packing results 63
30. Apparatus for measuring penetration 64
31. Apparatus for glass tube method of measuring changes in soil volumes 65
32. Apparatus for soil column method of measuring changes in soil volumes 66
33. Apparatus for micrometer method of measuring changes in soil volumes 68

MOISTURE CONTENT AND PHYSICAL CONDITION OF SOILS.

INTRODUCTION.

It is generally recognized that the physical properties of a soil determining crop adaptation and growth are moisture supply, aeration, temperature, texture and structure, and "physical condition." Under these heads fall practically all physical investigations on the soil. Of course "physical condition" is by far the most important in practice, because it is the one factor directly under the control of the agriculturist, such control of the others as may be possible being usually but incidental to control of the last. Everyone who has had any experience can judge with comparative readiness as to whether a soil is in good or poor physical condition. But apparently no two observers will agree entirely as to the basis of their judgments. It is said that a soil in good physical condition must be loose, friable, loamy, have a crumb structure, work well, have a "live" look, etc., properties which are sufficiently definite to be recognized readily, but which are not susceptible of exact measurement and quantitative expression. It is evident that a comparison of soils as to their physical condition is mainly a matter of individual judgment, subject to the limitations and errors of a personal equation; and while physical condition is the most readily under practical control, paradoxical as it may seem, it is the most difficult of soil properties to study. This is because the concept or idea of "physical condition" is a summation of a number of properties rather than any one property, and because no satisfactory method of measuring this sum has yet been devised. Nevertheless, much can be done to advance our knowledge of this important subject by studies in the field and, especially, in the laboratory.

In the present bulletin are given the results of an investigation on the relation of physical condition to moisture content, in which the soils were put into different states with different amounts of water present and then subjected to various physical tests yielding measurable results. In this work the judgment of several experienced greenhouse men was available for determining the physical condition of the samples before and after the several measurements were made. It has been found that the physical condition of the soil is connected

in the most intimate way with its water content. Not only is this true of its general behavior and appearance, its "workability," etc., but systematic quantitative measurements on penetrability, volume changes, apparent specific gravity, and rate of evaporation showed a direct dependence on the water content. All these properties varied regularly with regular change in the water content when the sample was in the best possible physical condition obtainable with any given water content.

One particular water content has been given special consideration. It is perfectly well known to agriculturists generally and greenhouse men especially that there is a particular water content (or perhaps a more or less narrow range of water content) differing with each soil at which plants grow best, other conditions being the same. This is popularly known as the "optimum" water content, and is supposed to be that content from which plants draw most readily their needed supply; in other words, the optimum water content is supposed to be determined by the physiological necessities of the plant rather than by the physical properties of the soil. There are difficulties, however, for which this view fails to offer sufficient and satisfactory explanation. Plants can do quite well in soils containing considerably less than the optimum water content, other conditions being favorable. That is to say, there is no decided or sharp falling off in the plant growth corresponding with a lowering of the water content until the drought limit is approached, a limit generally much below the "optimum;" and, on the other hand, there is no especial difficulty in carrying some of our common crops to a satisfactory maturity in water cultures. The investigation described in the following pages shows conclusively not only that physical condition and the several properties on which it depends have an intimate relation with the water content of the soil, but that there is marked accentuation in these properties at a critical water content; and that this critical content is identical with the optimum water content. The *moisture-penetration* curve shows a minimum force required for penetration at the optimum water content; the *moisture-apparent specific gravity* curve shows a minimum point at the optimum water content; the curves for *evaporation* show a marked difference in the rate of evaporation above and below the optimum water content. It is apparent, therefore, that the true significance of optimum water content is that particular content at which the soil can be put into the best possible condition for plant growth. The plant can then best draw its needed water from the soil because all the other factors making for good growth are also at their best. Moreover, an increase in water content in excess of the optimum generally produces a greater detrimental effect on the plant than a decrease below the optimum.

Furthermore, it should be borne in mind that practical men in bringing a soil to optimum water content judge when this point is reached by the appearance and "feel" of the soil; i. e., by the physical condition into which it can be brought, and not directly by any plant phenomenon. There is a widespread impression that the optimum water content for any one soil varies for different plants. That is, the *physiological* optimum, as determined by the plant, may not coincide with the *physical* optimum, as determined by the soil properties. While this may be true for certain exceptional cases, it is erroneous as regards the majority of common field crops, since the water content that makes for the best physical condition of the soil is as a necessary consequence the best for plant growth. Other evidence from experiments on wilting will be given in detail in support of this view. The available evidence seems to be conclusive that the problem of water supply and optimum water content is fundamentally a soil problem and incidentally a plant problem.

Another point which this investigation has brought out in a striking way is the "hysteresis" observable in the volume change when a soil is alternately wetted and dried out. This process results in a natural packing of the soil and is seriously detrimental to the maintenance of good tilth if the extremes of moisture content reached are wide apart. The causes for and mechanism of this process have been made clear by the experiments here recorded.

The importance in general farming of having a proper moisture content in the soil before plowing or other cultural operations is well known, although not always so well observed. It is regrettably common to find cases where the soil has been worked while too dry, and even more so are the cases where a soil has been worked while too wet, entailing disastrous results, requiring even years for rectification. These latter are the most baffling cases which the soil expert encounters.

The usual practice in irrigation gardening and greenhouse work of adding an excessive amount of water, so as to be on the "safe side," is far from the ideal soil management, and the working out of a better and at the same time an economical system of maintaining the water content constant, or approximately so, should be the aim of practical workers in these fields. It is believed that the data brought out in this bulletin will be of material assistance in understanding the phenomena involved in these difficult practical problems and in devising methods for the treatment and amelioration of lands which have been improperly handled.

In the course of this investigation a number of special methods and forms of apparatus were devised which it is believed will have a value not only for future investigation, but as a desirable part of the

equipment of a laboratory for student work. It has been deemed well, therefore, to give quite complete and detailed descriptions, and to this end the methods and apparatus are described and illustrated in a special chapter at the end of the bulletin, and only brief references to them are given in the text describing the investigations.

PENETRATION AND COHESION.

PREVIOUS WORK.

A property of the soil of recognized agricultural importance is *cohesion*, or the force with which the soil particles cling one to another. The previous work on penetration has been usually incidental to investigations of cohesion. This property has been studied because it is a determining factor of the ease of tillage and because it gives a measure of the physical condition of the soil and its variation under different treatments. In these studies two methods have been employed. In the one the crushing strength of cylinders of soil has been taken as a measure of the binding together, or cohesion, of the soil particles; in the other the "firmness" of the soil, which is due to its cohesion, has been determined by the resistance offered to the introduction of a sharp instrument. These latter investigations have been regarded of especial value in showing the relative resistance of different types of soils to tillage and root penetration.

Volker[a] applied the penetration method to actual measurements in the field, without, however, obtaining definite results. A penetration method was used by Meyer[b] in which four pegs fastened to the corners of a square were forced a definite distance into the soil by weights placed on the square surface. The crushing method was used in an investigation by Schübler,[c] who molded damp samples of soil into rectangular prisms. The samples were then either allowed to dry in the form or were removed while still damp and dried in the air or at a high temperature. The apparatus used to determine the crushing strength of the samples consisted of a beam supported on a fulcrum about one-third the distance from one end. On the long arm of this lever was hung a scale pan to which weights could be added gradually. At the opposite end of the beam was a counterpoise that balanced the scale pan and beam. On the long arm, a short distance from the fulcrum, a blade was fastened, free to move in the vertical plane of the beam. The dried soil sample was placed under this blade and weights added to the scale pan until the soil was either cut or crushed by the knife. The weight added was taken to

[a] Neue Moglinische Annalen der Landwirtschaft, 4, 119 (1818); ref. in Puchner, Forsch. auf dem Geb. Agr.-Phys., 12, 196 (1889).

[b] Anlage zur Flora des Königreichs Hannover (Göttingen), 307 (1822).

[c] Grundsätze der Agrikulturchemie, Leipzig, 2, 74 (1838).

represent the cohesion of the soil. The highest absolute cohesion value, that for pure clay, was taken as 100 and the other measurements compared with this. The series of relative values obtained for the different soils is shown in Table I.

TABLE I.—*Cohesion of dry soils, according to Schübler.*

Soil.	Cohesion of dry soil compared to clay.	Soil.	Cohesion of dry soil compared to clay.
Pure clay (kaolin)	100.0	Humus	8.7
Clay soil	83.3	Garden soil	7.6
Fertile clay	68.6	Gypsum	7.3
Barren clay	57.3	Calcareous soil	5.0
Hofwyl soil	33.0	Calcareous sand	0
Jura soil	22.0	Quartz sand	0

This table shows that clay in the dry form has a relatively high cohesion, while humus and lime soils are low, and sand does not bind together at all. By comparing some of the values obtained for the above soils with their mechanical analyses it was shown that in the clay soils the presence of humus or sand greatly reduces the cohesion.

This method is of interest in showing the binding qualities of very dry soils, yet it is open to the objection that the results obtained by it do not give reliable data for soils under ordinary cultural conditions. It is rare for field soils to dry out to an extent comparable with the condition reached in this method: and it will be pointed out later that the relative values for the cohesion of different soils vary with the quantity of water present. The table shows further that the cohesion value of sand is zero, which means that in drying out the sand samples did not retain their form. If the measurements are to give a basis of comparison for the ease of working the soils in the field, such a value is of course meaningless. A method which depends on an unsupported soil column is evidently too wide a departure from field conditions.

It is apparent that measurements of soil cohesion are not of great agricultural interest unless they take into account the variable quantity of water in a soil at different times, since this quantity plays a most important rôle in determining all of its physical properties. Extensive experiments in soil cohesion taking account of this factor were made by Haberlandt,[a] in which he measured cohesion by the crushing strength of cylinders. He also divided some of his soil samples into three fractions, depending on the size of the grains, and in this way he was able to study the relation between soil cohesion and size of the particles. In the method as first used by him he

[a] Wissenschaftlich praktische Untersuchungen auf dem Gebiete des Pflanzenbaues, Wien, 1875, Vol. I, p. 22.

molded cylinders of the soil in a glass tube one end of which was covered by a thin cloth. The cylinders and the glass tube were dipped in water to the depth of 1 centimeter and the soil allowed to take up moisture freely. The soil column, when removed from the glass tube, was 2 centimeters in diameter and 3 centimeters high. The cylinder was then allowed to dry until it had attained the desired moisture content, when the crushing strength was determined by placing a glass vessel on the top of the column and pouring in water until the soil gave way. From the weight of the vessel and water the value for the crushing strength was obtained in grams. The results for one soil are given in Table II.

TABLE II.—*Moisture-cohesion relations, according to Haberlandt.*

Grade of particles.	Moisture content.	Weight required to break down soil cylinders.
	Per cent.	*Grams.*
Coarse	32.6	120
	19.8	320
	13.1	725
	7.7	290
	2.4	170
Medium	25.9	225
	19.2	265
	16.8	500
	3.1	1,115
	1.2	1,080
Fine	33.4	450
	25.8	1,150
	7.0	1,900
	4.2	2,400
	1.9	4,200

From Table II it will be seen that the strength with which the particles are held together is greatly dependent on the moisture content of the soil. In two of the samples the cohesion value reached a maximum, indicating that in these soils a certain water content was of particular significance in regard to the cohesion. The soil with the finest particles became bound together more closely as it dried out, which is in agreement with the results of other investigators.

In another experiment Haberlandt studied the effect of mixing various quantities of sand and of moor soil with the sample of soil which was used in the previous experiment. As the percentage of sand increased the resistance to crushing diminished. This was likewise true of mixtures of the same soil with the moor soil.

In a later investigation Haberlandt[a] molded cylinders of the soil in a glass tube in the same way as before, and in addition to determining the crushing strength he measured the resistance to

[a] Forsch. auf dem Geb. Agr.-Phys., 1, 148 (1878).

breaking under a transverse load, by placing the soil cylinder across two parallel horizontal supports 6 centimeters apart. Midway between the supports a scale pan was suspended from the soil cylinder, and weights were added continually until the soil column gave way. The weight required was taken as a measure of the "absolute" firmness of the soil. The pieces of the broken soil column were cut down to the desired size and a measurement of the "relative" firmness was made by crushing the sample in the same manner as before described. Measurements were made on twelve different soils in which the values for "absolute" firmness varied from 115 to 3.5 and for "relative" firmness from 9,000 to 700. Compared by either method the soils fell in practically the same order.

The investigation was further extended by Haberlandt to determine the change in cohesion upon the addition of small amounts of charcoal and lime. The results are given in Table III.

TABLE III.—*Effect of lime and charcoal on cohesion, according to Haberlandt.*

Mixture.	Cohesion.
	Kilograms.
Untreated soil	31.4
Soil with 1 per cent charcoal	20.0
Soil with 1 per cent lime	8.9

The cohesion was reduced 36 per cent by charcoal and 72 per cent by lime. From his various experiments Haberlandt concluded: (1) The cohesion of different soils is widely different; (2) the cohesion depends on the size of the particles; (3) the cohesion of the soil is greatly diminished by the addition of lime, and this has a great influence in determining the ease with which soils can be worked in the field; (4) at some moisture content the cohesion is least for every soil. This last conclusion Haberlandt considered of great importance as bearing upon the question of the ease of working the soil in the field.

An extensive and valuable contribution to the literature of soil cohesion and penetration was made by Puchner,[a] who obtained values for "absolute" and "relative" firmness, both by the method of penetration and by a method similar to that of Haberlandt. The apparatus by which Puchner measured the penetration of soils consisted of a vertical shaft running through a metal guide. On the lower end of the shaft was fastened a penetrating knife blade 2 centimeters broad and 1 centimeter high, the angle of the cutting edge being 13°. The upper end of the shaft carried a scale pan to which weights were added directly until the blade was forced a required depth into the

[a] Forsch. auf dem Geb. Agr.-Phys., 12, 195 (1889).

soil. The unloaded shaft and scale pan were counterpoised by a weight running over a pulley. By means of a pestle the dry soil sample was packed into a dish having a perforated bottom to permit of saturation with water taken up by capillarity. This amount of water was taken to represent the total water capacity of the soil, or 100 per cent moisture content. The samples were then allowed to dry until they reached the moisture content desired, when the penetration was measured by the apparatus just described.

The influence of changing moisture content and that of size of particles on penetration were studied. For this purpose he used quartz sand separated into seven divisions, varying from 0.01 millimeter to 2 millimeters in diameter. The cohesion of these seven samples and a sample composed of all sizes was measured with varying water content. Experiments were also made on a calcareous soil (Kalksand), which was divided into four divisions, ranging from 0.01 to 0.25 millimeter. The results of these experiments are plotted in figure 1, the weight in grams necessary to force the blade the required distance into the soil being plotted as ordinate and the moisture content in percentage of dry weight as abscissa. The same abscissas hold for both the "Kalksand" and quartz curves. The numbers on the curves represent the limiting sizes of the particles. In order further to distinguish the curves representing the composite samples, they have been drawn in dotted lines. From these curves it is readily seen that the penetration values are greater for the finer particles and that the values for the composite samples lie between the extremes.

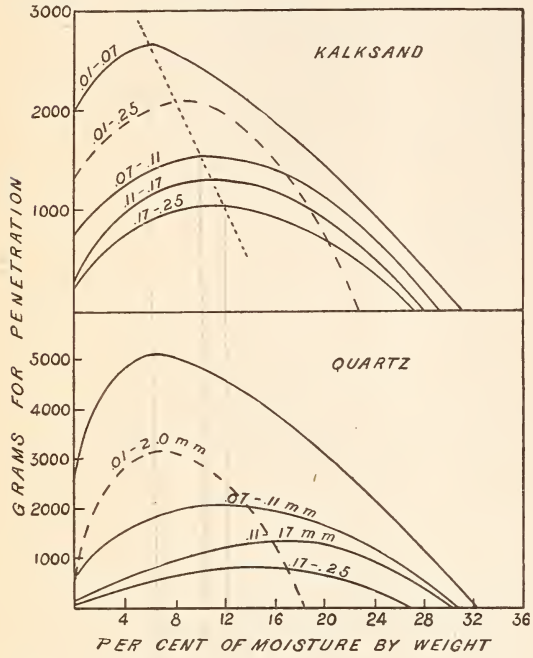

FIG. 1.—Influence of size of soil particles on penetration-moisture results for calcareous sand and for quartz, according to Puchner.

All these curves exhibit a maximum penetration value, from which it is evident that as the water content changes there is a corresponding change in at least this physical property, and that this

particular water content has a special significance. As the size of particles varies the position of the maximum changes. In the case of "Kalksand" this has been indicated by drawing a straight dotted line through the maxima. In the case of the quartz curves the maxima do not seem to bear so simple a relation to each other; this may be due to the fact that the composite sample contains many large particles (2 millimeters). Although there were seven divisions for quartz, only four of the corresponding curves are shown in the figure, since the curves for the larger sizes lie too close to the axis abscissas to be conveniently plotted.

The relation of penetration to changing moisture content was studied by Puchner with certain principal soil constituents (quartz, humus, and clay), and cohesion values were obtained for the pure substances and for their mixtures. In this work the measurements were limited to one range of particles between 0.01 and 0.14 millimeter. These results have been plotted in figure 2. The curves for kaolin and quartz, humus and kaolin, and quartz and humus are drawn in separate divisions and each has its own set of ordinates.

In the case of kaolin and the mixtures in which kaolin predominates the force necessary for penetration increases steadily as the soil dries out. In the other samples the penetration curves show again a maximum point. The curves are also interesting, since the absolute values for penetration of the pure substance and of mixtures may be compared directly.

In discussing the value of cohesion measurements made on dry samples alone as indicating the physical condition of agricultural land, it was pointed out that the results so obtained were likely to be misleading, since under field conditions we seldom have to consider a dry soil. The truth of this will become apparent on examining the curves. Taking, for example, the case of humus and kaolin in the dry condition, the cohesion values vary in the different samples from about 500 to 12,000 grams. Under favorable cultural conditions the mixture "1 humus+2 kaolin" would probably contain about 35 per cent water, while "2 humus+1 kaolin" might contain from 20 to 40 per cent; the pure humus would ordinarily contain from 70 to 90 per cent. At these moisture contents, which would represent fair field conditions, the cohesion values would not be very widely different.

In his experiments Puchner made observations on many other factors relating to penetration, such as the influence of "single grain" and "crumb" structure, addition of chemicals, plant covering, frost, etc., to some of which reference will be made later. He also made quite as complete a study of soil cohesion by measuring the crushing strength of cylinders of his soil material, from which he obtained the same results and reached the same general conclusions, as follows:

(1) The cohesion of the soil, i. e., the force with which the soil particles are bound together, depends on the physical constitution of the soil, on the moisture content, and on the presence of various salts.

(2) Of the different soil constituents, clay has the greatest binding strength, while that of quartz, humus, and lime is less. The cohesion of the soil will therefore depend on the relative proportions of the different materials.

(3) The influence of water on the cohesion of soils is of great importance. In clay and clay earth the cohesion is greater as the water content diminishes,

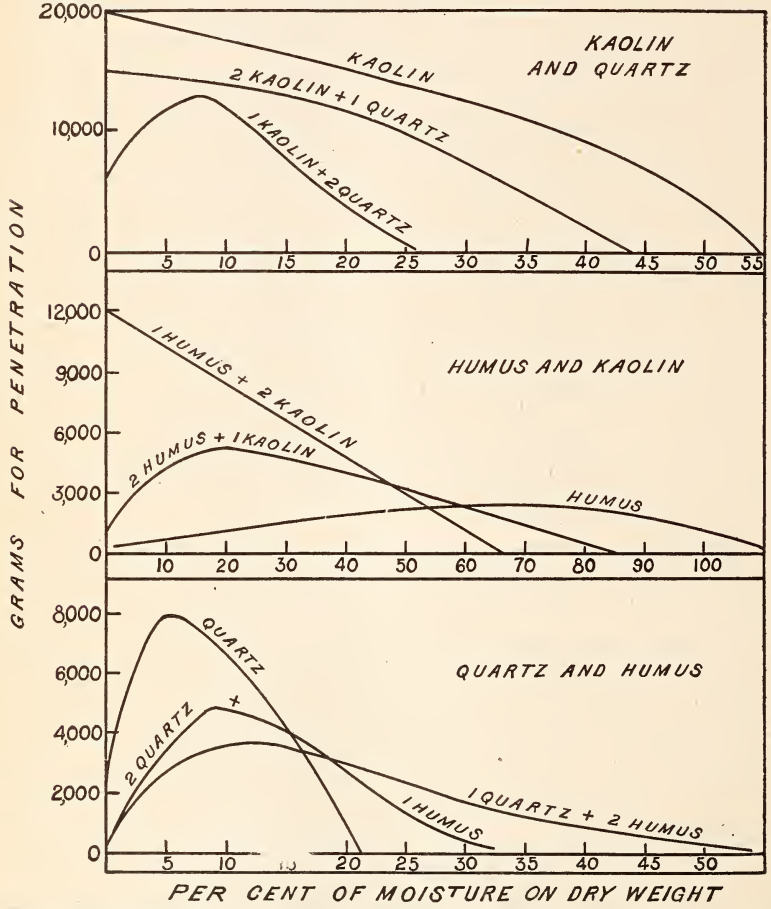

FIG. 2.—Penetration-moisture results for different soil components and mixtures of them, according to Puchner.

while in humus, quartz, and lime the soil particles are most strongly held together at a medium percentage of water.

(4) The cohesion in any soil depends on the internal arrangement of the particles. It is greater in a "single grain" structure than in the "crumb" structure. If the soil particles are pressed together by an external force there results a proportional increase in the cohesion.

(5) Under otherwise similar conditions the binding strength of the soil is greater under crops than in fallow.

(6) The freezing of the soil greatly raises the absolute firmness.

(7) On the addition of lime the cohesion of clay is reduced under all moisture conditions, while the addition of potassium hydroxide and potassium carbonate increases the cohesion when the soil is dry, but reduces it at higher moisture content.

(8) In a consideration of the moisture condition most favorable for working a soil and best suited to placing it in most favorable mechanical condition, the question of cohesion should not enter, since with a medium water content (somewhere about 40 per cent of the total water capacity) the cohesion of most soils is at a maximum, and the soil can then be worked more easily into a crumbly condition. It is desirable to obtain the crumb structure, which is the best physical condition of the soil—i. e., the condition most favorable for crop production—even at the expense of greater labor.

It is quite evident from the work of other investigators that the cohesion or binding power is quite different for different soils and that it determines the penetrability. It is a matter of particular interest that the penetrability is closely connected also with the amount of moisture in soils. In order to investigate the influences of water on the physical condition and on the productiveness and apparent fertility of soils, a further study on penetration has been made.

RELATION OF PENETRATION TO MOISTURE CONTENT.

Object of experiments.

Unlike previous investigations in soil penetration, these measurements were not made primarily to study soil cohesion or to determine the resistance offered by various soils to cultural treatment. The purpose was rather to determine what constitutes a favorable physical condition for plant growth and how water affects this condition. It was assumed that the soil could be put into a most favorable condition as a cultural medium and that penetration measurements could be taken tentatively as an index of this state.

These considerations had an important bearing on the development of the methods used. It was pointed out by Puchner that a soil can best be put into a crumbly structure when it contains a medium amount of water. The importance of a crumb structure as a soil condition has long been known to agricultural men, and is earnestly sought in good agricultural practice. The ability of a soil to build a crumb structure or to form itself into aggregates is an important factor, determining the value of that soil as a medium for plant growth. The penetration work in previous investigations of soil cohesion has not been conducted under conditions best suited to plant growth. In fact the experimental procedure usually put the soil samples in a condition much worse than obtained in field practice. The soils were packed when dry, often with a pestle, so that the individual grains were worked into very close contact with each other, and the soils were then completely saturated with water, the samples being thus

packed still closer. The desired water contents at which measurements were made were obtained by letting the saturated samples dry out. Such a procedure could hardly be said to duplicate field conditions. In order to study the influence of water upon the soil as a cultural medium it was desired to put every sample of soil into the most favorable state possible.

Experimental methods.

Neither absolute values for penetration, nor the comparison of these absolute values for different soil types were attempted; but rather the aim was to determine the variation in the penetration values for one particular soil at different moisture contents. Furthermore, a comparison of the penetration values for different soils can not be made, on account of frequent changes in the apparatus during the course of the investigation. No such variation as this, however, occurs during a set of measurements on any one soil sample, and these results are strictly comparable with one another.

In this problem one of the most serious difficulties encountered was so to control the handling of the soil sample and its packing that an agreement in results could be obtained between duplicate experiments. The difficulty in regulating the packing was rendered greater by the fact that the soils were to be examined in a loose condition, in which state even slight changes in the packing force produce large variations in the results. In studying the change of penetration with varying water content it was desired that all soil samples should have the same treatment. This it was impossible to do so long as the samples were worked by hand, and it was only possible when the process of packing was made purely mechanical. To this end a power-driven shaker (see fig. 27, p. 60) was devised, in which the soil samples were run through a coarse screen, after which they fell a definite distance through a funnel into the dish in which the penetration measurement was to be made. Since the screening was mechanical and the same in each case, the packing could be changed by varying the height through which the soil fell.

The apparatus for measuring the penetration (see fig. 30, p. 64) consisted of a long lever arm from the end of which was suspended a sharp conical tool of steel, free to swing in the vertical plane of the lever beam. This tool was forced a definite distance into the soil sample by weights added gradually to the middle of the beam. The unloaded beam and attachments were balanced by a counterweight hung beyond the fulcrum on the opposite end of the lever.

In making a penetration measurement the procedure followed was to make up a soil sample to about the desired moisture condition. The sample was run through the screening machine into the dish in which the penetration measurement was to be made. This dish was large enough so that several measurements were made on each sample,

the mean of which was taken to represent the final value. The data for the complete variation of the moisture content were usually obtained by starting with air-dry soil. After the penetration value for this sample was obtained, enough water was added to the same lot of soil to increase the moisture content by a few per cent. This sample was in turn screened and measured, as before. The moisture content was thus gradually increased and measurements taken until the soil became too moist to work. The process could be reversed with equal success by letting the wet soil dry out to the desired point as long as the sample was screened at the same moisture content for which the penetration was determined. The amount of water present in the soil at each measurement was determined by drying a sample of the soil at 110° C. and calculating the moisture content to the dry weight, since this method gives moisture values which for any one soil are directly proportional to the actual amounts of water present. This method does not, however, give any idea of the moisture relations when comparison is made between different soils.

Results for Podunk fine sandy loam.

The first measurements of penetration were made for Podunk fine sandy loam, the mechanical analysis of which is given in Table IV.

TABLE IV.—*Mechanical analyses of Podunk fine sandy loam.*

Name of division.	Limits of size.	Percentage.	Name of division.	Limits of size.	Percentage.
	Millimeters.			*Millimeters.*	
Fine gravel	2.0 —1.0	0.0	Very fine sand	0.1 —.05	30.4
Coarse sand	1.0 — .5	.0	Silt	.05 —.005	18.8
Medium sand	.5 — .25	1.0	Clay	.005—.0	2.2
Fine sand	.25— .1	47.6			

This soil is seen to consist very largely of fine sand and very fine sand, along with considerable silt. It proved to be a soil particularly well adapted to an investigation of this kind, being very easy to work and not becoming sticky when water was added to it. In the air-dry condition it was found to hold about 0.3 per cent of water, and when completely saturated by letting water rise by capillarity into short columns it held about 30 per cent. The results of a series of penetration measurements on this soil are given in Table V.

TABLE V.—*Penetration-moisture relations for Podunk fine sandy loam.*

Moisture content.	Weight required for penetration.	Moisture content.	Weight required for penetration
Per cent.	*Grams.*	*Per cent.*	*Grams.*
0.36	142	7.9	33
.92	73	10.5	38
3.9	28	13.1	42
5.8	28		

These results are shown graphically in figure 3, where the water content is measured on the axis of abscissas and the weight required for penetration on the axis of ordinates.

It can be seen from this that when the soil is put into the loosest possible condition the penetration measurements give a minimum between 4 and 6 per cent of water. This would indicate that as the moisture in the soil changes there is a definite variation in this physical property, and that one particular range of water content seems to have a special significance. It makes no difference in the result whether the water content be changed by adding water to the soil or by drying out a wet soil, for at one and the same moisture content the penetration value is a minimum.

As was pointed out in the introduction, there is a moisture condition in each soil which is recognized as the "optimum" water content, and is determined by the "feel" of the soil. To determine whether there is a relation between the critical amount of water as found in the above penetration work and this optimum water content, several samples of Podunk fine sandy loam, containing different amounts of moisture, were made up to optimum condition by practical greenhouse men. When the moisture determinations of the samples were made they were between 5 and 7 per cent of water, thus suggesting that the minimum in the penetration curve has a casual connection with the optimum water content, a quantity which up to this time has been purely arbitrary.

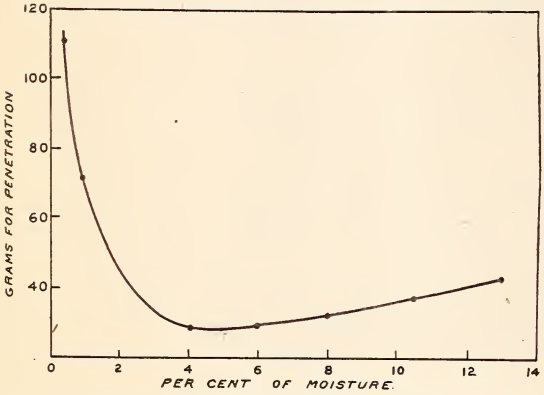

FIG. 3.—Penetration-moisture results for Podunk fine sandy loam.

Another set of penetration-moisture results, obtained in a similar manner except that the packing was somewhat greater, is given in Table VI.

TABLE VI.—*Penetration-moisture relations for Podunk fine sandy loam.*

Moisture content.	Weight required for penetration.
Per cent.	*Grams.*
0.3	178
2.6	53
6.0	48
11.6	54

These results are like the others in that they show a minimum at about 6 per cent of moisture content.

In working this soil preparatory to the measurements a great difference was noticed in its behavior as the amount of water was changed. The air-dry sample was of course in poor condition for agricultural purposes and was quite difficult to work because of the dusty nature and the compact state into which it settled. The addition of very little water produced a great change, as might have been predicted from the penetration curve; and although the soil was too dry for agricultural purposes, it was no longer dusty, seemed much lighter, and it screened and packed better. The soil sample giving the least penetration value responded most readily to working; it screened well, felt damp, light, and of an even texture. Beyond this point the soil began to feel wet and to show the effects of what might be called "free water"—i. e., water which does not seem to be an integral part of the soil. At 10 per cent water content the soil was still in fairly good condition, although it screened rather slowly, and beyond 14 per cent it could not be worked because of the difficulty of screening the wet soil. At this point it was evident that the soil was too wet for good plant growth. Although this method does not permit a study of soil condition in the neighborhood of the saturation point, it does allow sufficient variation to cover the range of soil moisture usually met under growing conditions, a range extending well above and below the optimum water content.

The penetration values according to this method form an interesting comparison with the plant growth on soils containing varying quantities of moisture. In the air-dry condition the soil is not able to sustain crops. When enough water has been added to the soil to enable it to support plant life, the penetration values drop very rapidly and are of the same order of magnitude as found at the minimum point. Beyond the minimum the penetration for Podunk fine sandy loam rises very slowly, which may be interpreted to mean that the physical condition of this soil changes but slightly over a range of several per cent, for the soil remains in very fair condition for plant growth over quite a wide range above 6 per cent of moisture.

It will be remembered that in his work on soil cohesion Puchner obtained maxima in his penetration-moisture curves, while the results just described showed minima. Puchner attributed his maximum values to an increase in the soil cohesion due to the presence of a definite amount of water in the soils. He also pointed out that this particular amount of water in the soil was most favorable for the formation of floccules or soil aggregates and the attainment of a crumb structure, due to this same increased cohesion. This appears to connect his observations with those here recorded and to show that the same forces which caused a maximum under the one method of

procedure operated under a very different method to give a minimum. In order to test this point, a penetration-moisture study was made on Podunk fine sandy loam under conditions similar to those of the Puchner method. The results obtained are given in Table VII and graphically represented in figure 4. In order to make this result more easily comparable with other penetration results, we have included in the figure, using the same abscissas, a curve obtained for the same soil by the regular method of loose packing. Each curve, however, is given with its own ordinates. Although the penetration value for the critical point exhibited by the maximum is over one hundred times as large as the value given by the penetration at the minimum, and although the methods are widely different and represent very different conditions of internal arrangement of the soil particles, the agreement of the critical points in regard to the water content of the soils is very striking indeed. From this it is evident that in a soil some particular water content is of marked importance in determining the physical character of the soil, which property is undoubtedly determined by the distribution of the water.

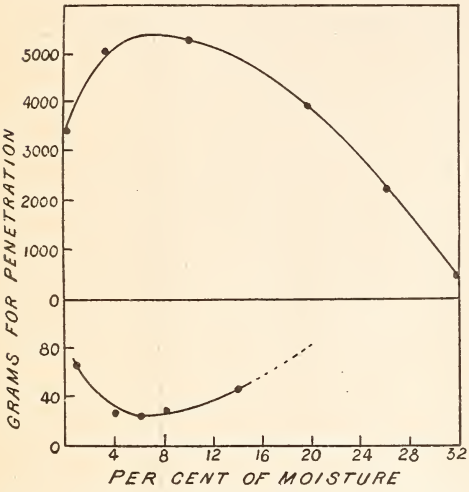

FIG. 4.—Penetration-moisture results for Podunk fine sandy loam by method of Puchner and by method of loose packing.

TABLE VII.—*Penetration-moisture relations for Podunk fine sandy loam, by the Puchner method.*

Quantity of water in soil.		Weight required for penetration.
Proportion of dry weight.	Proportion of total water capacity.	
Per cent.	*Per cent.*	*Grams.*
32.0	100.0	532
26.0	81.0	2,320
19.4	60.8	4,080
8.6	26.8	5,300
2.7	8.5	5,052
.0	.0	3,400

At the same time some experiments were made on the variation in the penetration-moisture relations when the soils were packed under different pressures. These results have a special interest in connection with the forms of the curves obtained by Puchner's method and by our method. In studying the effect of packing the soil, samples of Podunk fine sandy loam were prepared in the regular manner of loose packing, except that before the penetration measurement was made the desired pressure was applied to the surface of the soil by means of an apparatus designed for that purpose (see p. 62). The results of these measurements are given in Table VIII, and shown graphically in figure 5. The amount of the pressure per square centimeter used in packing the soil is given on each curve.

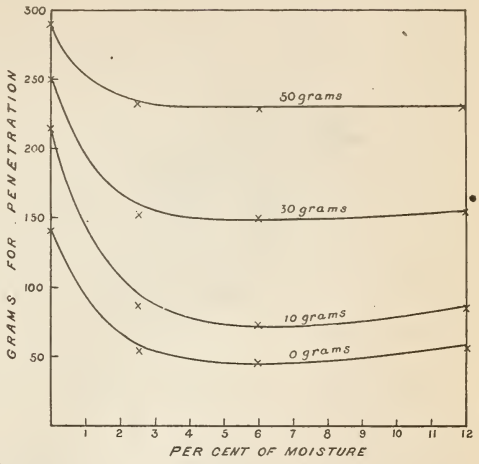

FIG. 5.—Penetration-moisture results with different packings.

TABLE VIII.—*Penetration-moisture relations for Podunk fine sandy loam, packed under different pressures.*

Packing force per square centimeter.	Moisture content.	Weight required for penetration.	Packing force per square centimeter.	Moisture content	Weight required for penetration.
	Per cent.	*Grams.*		*Per cent.*	*Grams.*
0 gram	0.0	178	30 grams	0.0	250
	2.6	53		2.6	155
	6.0	48		6.0	150
	12.2	54		12.2	154
10 grams	.0	237	50 grams	.0	291
	2.6	84		2.6	232
	6.0	72		6.0	230
	12.2	82		12.2	230

Although the pressures applied are not large and do not raise the penetration values anywhere near the point reached by samples measured according to Puchner's method, yet there is a well-defined tendency for the curves to flatten out as more pressure is applied. There is much less difference between the penetration values of the minimum and the dry state in the sample packed under 50 grams than there is in the sample packed under 10 grams pressure. The difference in the results obtained in the two penetration methods discussed is ob-

viously one of packing. It would seem that upon increasing the pressure used in packing the loose samples a series of curves would be obtained ranging from those by our method, showing a minimum, to those by the Puchner method, showing a maximum. It was not deemed advisable at the present time to investigate this point further.

Results for Miami black clay loam.

Having found the above results for a sandy soil of low water capacity and poor in organic matter, the same method of study was applied to the Miami black clay loam, a soil of widely different character, a silty soil rich in organic matter, having a large capacity for water. The mechanical analysis of this soil is given in Table IX.

TABLE IX.—*Mechanical analysis of Miami black clay loam.*

Name of division.	Limits of size.	Percentage.	Name of division.	Limits of size.	Percentage.
	Millimeters.			*Millimeters.*	
Fine gravel	2.0 –1.0	1.2	Very fine sand	0.1 –0.05	6.2
Coarse sand	1.0 – .5	7.6	Silt	.05 – .005	53.4
Medium sand	.5 – .25	3.9	Clay	.005– .0	11.6
Fine sand	.25– .1	16.1			

The total water capacity of this soil is about 60 per cent, and in the air-dry condition it ordinarily contains about 8 per cent of moisture. When this soil was made up to optimum water content by field methods it was found to contain from 35 to 40 per cent of water.

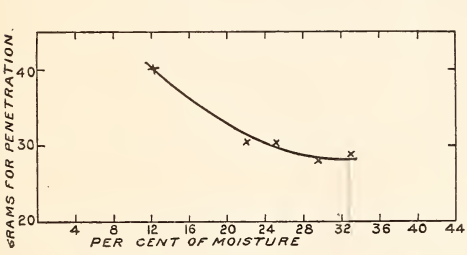

FIG. 6.—Penetration-moisture results for Miami black clay loam.

A penetration-moisture curve was made for Miami black clay loam when the soil was put each time into the loosest possible condition, the method being the same as already described for Podunk fine sandy loam. The results are shown graphically in figure 6.

When water was added to a comparatively dry sample the penetration value dropped to a minimum at 32 per cent moisture content. Enough water was added to the 32 per cent sample to increase the water content by several per cent, whereupon the soil proved too sticky to screen well. At 32 per cent the soil was in excellent condition, but on account of its clayey nature a few per cent of water caused a great change in the "workability." From this curve it is evident that as water is added to the dry soil, the cohesion is increased and the soil can be worked into aggregates. When the cohesion of the soil is greatest, as evidenced by a minimum in the penetration curve, the soil is in excellent physical condition.

Results for Leonardtown loam.

The next soil studied was quite different from those previously described, being a light-colored soil containing considerable clay and little organic matter, becoming rather sticky when wet, and on drying setting in a hard condition. The optimum water content for this soil was found to lie at about 15 per cent, a value midway between the optimum water content of the Podunk fine sandy loam and that of the Miami black clay loam. In the air-dry condition the soil contains about 1.3 per cent of water and when saturated holds some 34 per cent Several concordant sets of penetration results were obtained for this soil. Despite its tendency to become sticky when wet, it was possible to carry the penetration curve some distance beyond the optimum water content. Table X and figure 7 show the results of one set of

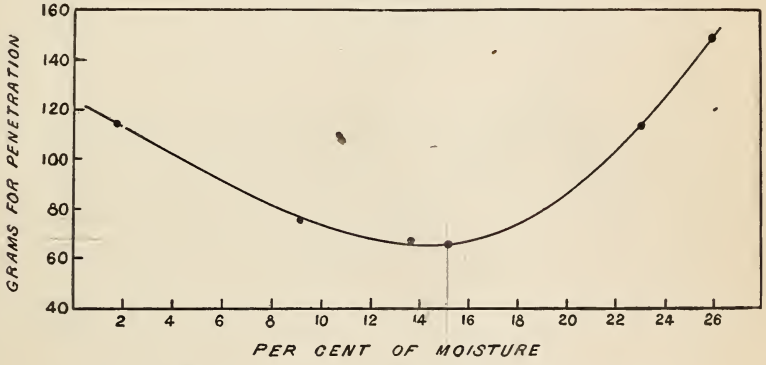

FIG. 7.—Penetration-moisture results for Leonardtown loam.

measurements. The curve drops to a well-defined minimum at about 15 per cent of moisture, which is also the optimum water content.

TABLE X.—*Penetration-moisture relations for Leonardtown loam.*

Moisture, calculated on dry weight of soil.	Weight required for penetration.	Moisture, calculated on dry weight of soil.	Weight required for penetration.
Per cent.	*Grams.*	*Per cent.*	*Grams.*
1.7	115	15.2	66
9.1	75	23.1	115
13.7	68	25.9	150

It was pointed out in the case of Podunk fine sandy loam that the form of the penetration curve might serve as an index to the character of the soil, and that for several per cent beyond the optimum water content the penetration curve rose very slowly, indicating that the physical properties change slowly and that the soil remains in fairly good agricultural condition. The penetration curve for

Leonardtown loam rises sharply, indicating a more marked change in the physical condition of the soil. Here also the curve corresponds to the field observations, for the favorable soil condition existing at 15 per cent of water rapidly disappears with a slight increase of water content. Further data on penetration for this soil are given in Tables XXIII and XXIV.

Results for Muck.

The next soil was studied as a check upon the conclusions reached in the previous work because it is an extreme soil type, being composed largely of organic matter and having a high water content. The mechanical analysis of this soil is not presented, as it would give

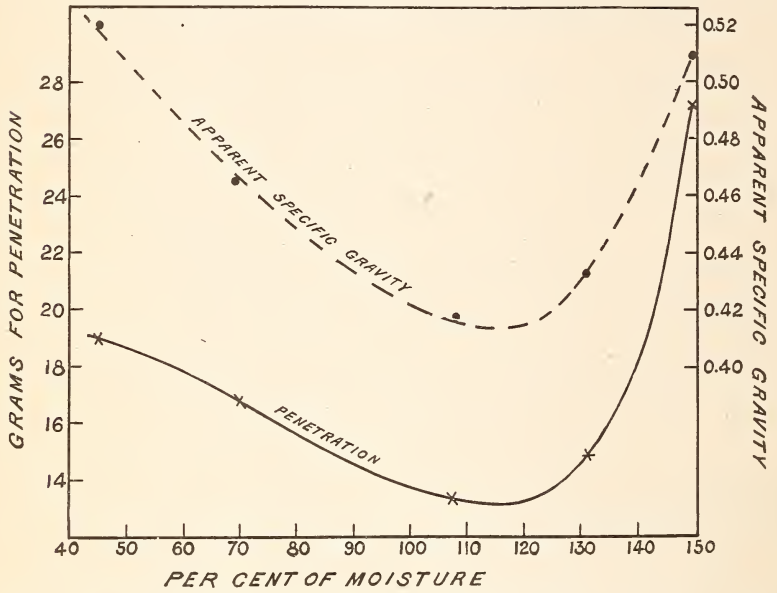

FIG. 8.—Penetration-moisture and apparent-specific-gravity-moisture results for Muck.

little indication of the soil texture owing to the large quantity of organic matter present. In the air dry condition this soil ordinarily holds about 45 per cent of water, and when saturated some 220 per cent. The soil is in good condition for agricultural purposes over quite a wide range of moisture content, and it would be difficult to assign a close limit for the optimum water content as determined by the ordinary field method; however, it may be considered as between 120 and 140 per cent. The penetration measurements were made in the usual manner, the results being given in figure 8. From this it is seen that the penetration value reaches a minimum at about 120 per cent of moisture, which agrees well with the optimum water content.

APPARENT SPECIFIC GRAVITY OR VOLUME.

PREVIOUS WORK.

In 1838 Schübler[a] studied the volume changes of soil by drying out wet samples until the weight no longer decreased. Representing the original volume as 1,000, he gives the volume to which the soils contracted on drying. In this way a comparison was obtained between different soil types. The results are shown in Table XI.

TABLE XI.—*Volume changes of soils on drying, according to Schübler.*

Material.	Percentage of original volume.	Material.	Percentage of original volume.
Quartz sand	100.0	Clay	88.6
Calcareous sand	100.0	Ordinary field soil	88.0
Gypsum	100.0	Fertile garden soil	85.1
Slate marl	96.5	Magnesium carbonate	84.6
Calcium carbonate	95.0	Kaolin	81.7
Potters clay	94.0	Humus	80.0
Clay loam	91.1		

The diminution of volume on drying was determined for six soils by Wolff,[b] who measured the change by means of a graduated cylinder. The influence of the size of the particles on the volume changes in soil was first studied by Haberlandt.[c] He used twelve soil samples, each of which was divided mechanically into ten separations. From the change in volume of the different soils and the water capacity, humus content, and mechanical analysis, conclusions were reached regarding the influence of different soil constituents on the volume changes. The experimental method consisted in measuring the change in volume of soil cylinders made from the damp earth. Haberlandt came to the following conclusions:

(1) The volume change which different closely packed soils undergo in drying out from a wet condition varies from 0 to 20 per cent of the original volume.

(2) Such volume changes are measured best in closely packed soils; loose soils are not well suited to measurement.

(3) Of the soil constituents humus has the most influence on volume change.

(4) It is probable that the volume changes of soils bear a linear relation to the fineness of the particles; yet this is only the case when these fine particles all have the same power to swell.

The volume changes due both to drying out and wetting were studied by von Schwarz.[d] He used four soil samples the mechanical analyses of which are given in Table XII. The volume changes are given in Table XIII.

[a] Grundsätze der Agrikultur-Chemie. Leipzig, II, 82 (1839).

[b] Anleitung zur chemischen Untersuchung landwirtschaftlich wichtiger Stoffe, Berlin, 1899.

[c] Fühling's landw. Ztg., **7**, 481 (1877).

[d] Erster Bericht über Arbeiten der k. k. landwirtschaftlichen Vers.-Stat. in Wein (1870–1877), p. 51.

TABLE XII.—*Mechanical analyses of soils used in volume studies by von Schwarz.*

Soil type.	Sands.				Suspended material.
	Coarse.	Medium.	Fine.	Very fine.	
	Per cent.	*Per cent.*	*Per cent*	*Per cent.*	*Per cent.*
1. Sand	0.0	96.34	3.11	0.55	0.55
2. Loam	0.0	19.87	31.70	30.39	18.04
3. Clay	0.0	0.0	0.0	4.53	95.47
4. Moor	Contained 82.6 per cent organic matter.				

TABLE XIII.—*Volume changes of soils on drying, according to Von Schwarz.*

Soil.	Decrease on drying.	Increase on wetting.
	Per cent.	*Per cent.*
1. Sand	0.0	0.0
2. Loam	17.0	19.2
3. Clay	29.8	42.4
4. Moor	60.2	.....

An extended study of the volume changes on wetting and drying soils was made by Wollny.[a] In the apparatus devised by him for this study the soil samples were contained in a wide cup with a perforated bottom. This was surrounded by an outside dish so that the samples could be wetted by capillary water. On the surface of the soil rested a metal plate to which an upright rod was fastened. The weight of the rod and plate was counterbalanced by a weight running over a pulley. The upper part of the rod was notched so that it constituted a part of a rack and pinion that, on moving, revolved a pointer on a circular scale. The soil to be measured was packed into the containing dish in the dry state, the surface leveled, and the plate which moved the measuring mechanism was adjusted to the surface. By allowing the wet soil to dry, another measurement could be made. A measurement of the relation of volume change to size of particles on drying a soil gave the results in Table XIV.

TABLE XIV.—*Volume changes on drying soil separates, according to Wollny.*

Soil (quartz sand).	Size of particles.	Decrease in volume due to drying.
	Millimeter.	*Per cent.*
I	0.01–0.07	0.99
II	.07– .01	.17
III	.11– .17	.15
IV	.17– .25	.11
V	.25– .50	.0

From this table it follows that the change of volume in quartz sand is greatest for the finest material. Similar results were obtained

[a] Forsch. auf dem Geb. Agr.-Phys., **20**, 1 (1897).

when the dry soil samples were wet, although in this case the volume changes were greater, as can be seen from Table XV.

TABLE XV.—*Volume changes on wetting soil separates, according to Wollny.*

Soil (quartz sand).	Size of particles.	Increase in volume due to wetting.
	Millimeter.	*Per cent.*
I	0.01–0.07	8.01
II	.07– .11	5.09
III	.11– .17	1.25
IV	.17– .25	.78
V	.25– .50	.0

Measurements were made on drying and wetting the principal soil constituents—quartz, clay, and humus, and their mixtures. The quartz used in this work was the finest size, varying from 0.01 to 0.07 millimeter. Table XVI gives the values obtained both in drying and wetting the samples.

TABLE XVI.—*Volume changes of different soil constituents and their mixtures due to changing moisture content, according to Wollny.*

Soil mixture.	Decrease on drying.	Increase on wetting.
	Per cent.	*Per cent.*
Kaolin	39.92	36.92
Kaolin, 2 parts + quartz, 1 part	33.17	30.90
Kaolin, 1 part + quartz, 2 parts	20.63	19.28
Quartz	.99	8.01
Quartz, 2 parts + humus, 1 part	2.86	10.84
Quartz, 1 part + humus, 2 parts	4.58	14.07
Humus	5.39	15.92
Humus, 2 parts + kaolin, 1 part	23.63	25.22
Humus, 1 part + kaolin, 2 parts	35.19	32.79

From this it is to be concluded that the volume changes in a soil are greater the more clay there is present and less the greater the amount of quartz. The humus causes an increase in the volume change when mixed with quartz, but has an opposite influence in mixtures of clay.

A number of other factors that influence volume changes in soils were studied by Wollny, such as effects of hydrates and salts, the effect of the arrangement of the soil particles, and the effects of rainfall and freezing, to some of which further reference will be made in the following pages.

RELATION OF VOLUME TO MOISTURE CONTENT.

Object of experiments.

From the work on volume changes just reviewed it is evident that variations in volume of greater or less magnitude occur in all soils when wetted and dried, which changes are influenced by a number of factors. The relation between the magnitude of these changes had

been well established for a number of soils and under a number of different conditions. In none of the work, however, is there any reference to the variation in volume with the variation in moisture content. What has been measured may be designated the "total" change, which represents the difference in volume between the saturated and the air-dry conditions. Whether all or the greater part of the variation occurs over the range of low percentage of water or near the saturation point, or whether it is equally distributed over the entire range of moisture variation, has not been determined. In studying the effect of different amounts of water as affecting the physical state of the soil and determining favorable conditions for plants, it is of particular interest to know whether special quantities of water have a determining influence on the physical properties.

Variations in water content have all been in one direction, from the wet to the dry state, since there is no satisfactory way of adding regular intermediate percentages of water to a soil and leaving it in place for measurement. A soil could of course be molded into any convenient shape, saturated with water and measurements on the volume of the sample made as the water content decreased, without in any way disturbing the soil sample. The parallel results obtained by Wollny in the measurement of the "total" volume change in wetting and drying out a sample, indicate that the determinations in drying out a sample will probably give a true idea of the nature of the changes occurring.

Experimental methods.

Several different methods were used to measure the change in volume, because it was desired to have check methods and because different soil samples did not lend themselves equally well to the same method. The contraction along one dimension was measured rather than the actual volume change. The assumption was made that the contraction was the same in all directions and from the linear change for unit length the percentage volume decrease was calculated from the formula $D=1-(1-x)^3$, where x represents the unit linear change.

In one method, which will be designated the "soil column method,"[a] a cylinder of soil was supported in an inclined position on a metal form made by sawing a brass tube in half, longitudinally. A cylindrical brass follower was brought in contact with the upper end of the soil column. As the wet soil column dried out and diminished in length the brass follower moved downward, and this movement was measured by means of a micrometer screw, reading to 0.001 centimeter.

[a] For full description see p. 67 and fig. 32.

This same micrometer was used at a different time to measure the contraction of samples contained in vertical glass tubes (see p. 65 and fig. 31) where a follower was also used in connection with the soil surface. This method will be designated as the "glass-tube method."

A different micrometer screw, reading to 0.0001 centimeter, was used in another method, where the soil sample was held in a cylindrical dish (see p. 68 and fig. 33), through the perforated bottom of which the sample could be saturated with water. A brass disk was set on the surface of the soil and the micrometer point brought in contact with this. For convenience this method will be designated the "micrometer method." A cathetometer was used to follow the contraction in soil samples supported in containing vessels having perforated bottoms. The point of an upright shaft, supported by a disk resting on the surface of the soil, was focused on the cross lines of the cathetometer telescope and thus the variation in the height of the soil surface was followed. This method will be called the "cathetometer method."

As a further indication of volume changes the apparent specific gravity of the soil was measured by weighing a unit volume in the condition in which it was worked. These observations were made at the same time that the penetration work was being carried on. In determining these data for the various soil samples it was necessary to level off the dish carefully, weigh dish and soil, and divide the weight of the soil by the volume of the dish.

Results for Podunk fine sandy loam.

It has been shown above that at a certain percentage of water the penetration results indicate that it is possible to work the soil into a maximum "looseness," which amount of water corresponds to the optimum water content. This observation was further checked by measuring the apparent specific gravity of the soil—the results being given in Table XVII.

TABLE XVII.—*Apparent specific gravity-moisture relations for Podunk fine sandy loam.*

Moisture content.	Apparent specific gravity.	Moisture content.	Apparent specific gravity.
Per cent.		*Per cent.*	
0.36	1.31	7.9	0.665
.92	1.21	10.5	.722
3.9	.69	13.4	.777
5.8	.655		

These data are better illustrated by the curve in figure 9, from which it is seen that the variation of apparent specific gravity with moisture content corresponds closely with the penetration-moisture

results. On account of the greater accuracy attainable by weighing, the data given by the apparent specific gravity variations are even more concordant than those given by penetration measurements, which are more difficult to make with accuracy on account of the influence of small irregularities in packing.

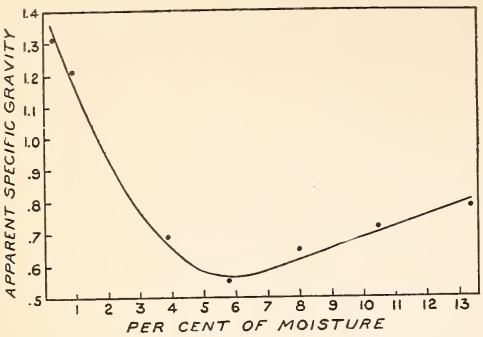

FIG. 9.—Apparent-specific-gravity-moisture results for Podunk fine sandy loam.

The apparent-specific-gravity data obtained in connection with the penetration measurements made when the soil was subjected to different packing pressures are shown by means of the curves in figure 10,

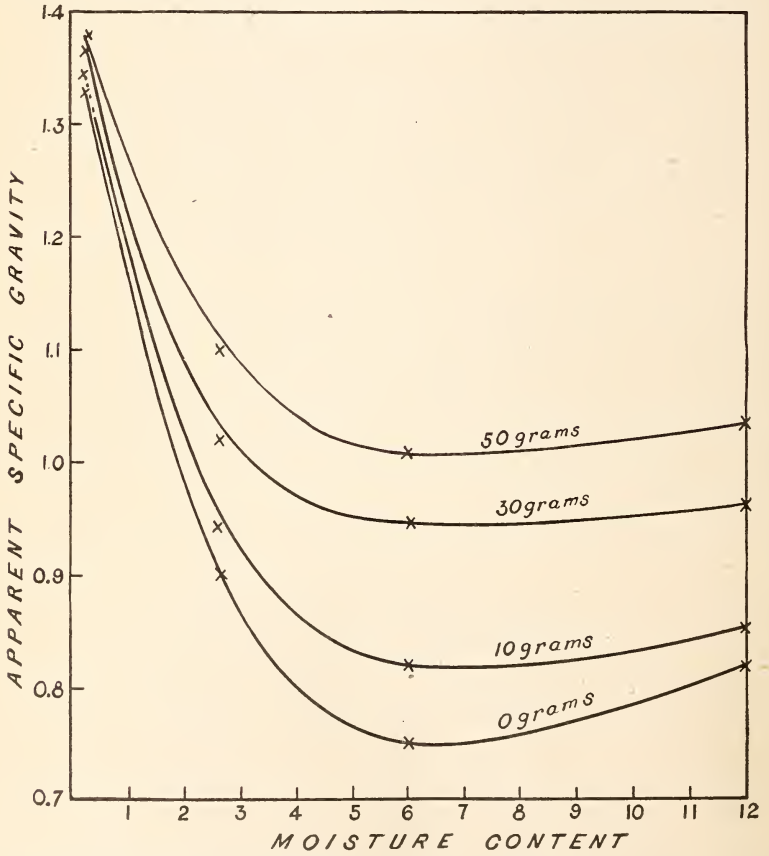

FIG. 10.—Apparent-specific-gravity-moisture results for Podunk fine sandy loam with different packings.

where the numbers on the curves represent the packing force per square centimeter. These curves are similar to the corresponding penetration curves, but they indicate more clearly the tendency to flatten out under increasing pressure due to the fact that the specific gravities of the dry samples are much closer together, so that the results of packing the loose soils at the optimum water content are more marked.

It can be readily seen from the work of Wollny on the "total" change of volume of soils that the measurement of the change of volume in sand with varying moisture content would present exceptional difficulties on account of the very small change of volume. When it is borne in mind that the volume is a cubical function of one length, the difficulty of obtaining accurate measurements on the linear contraction can be appreciated. In comparison with the readiness with which contraction measurements were made on some soils, the study of the volume change in Podunk fine sandy loam presented serious experimental difficulties. But these results were essential in order to compare the variations in this physical property with the changes in penetration and apparent specific gravity already given, and to complete a correlation of the individual properties that are dependent on the moisture content of the soil.

The results of a series of measurements on the volume changes in Podunk fine sandy loam as made by the micrometer method are given in Table XVIII.

TABLE XVIII.—*Volume-moisture relation for Podunk fine sandy loam.*

Moisture content.	Linear decrease.	Volume decrease.	Moisture content.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
32.9	0.0	0.0	11.5	0.022	7.13
29.8	.006	1.98	9.7	.022	7.13
29.0	.007	2.19	8.2	.022	7.13
27.7	.011	3.6	6.8	.022	7.13
22.7	.021	6.87	6.4	.0225	7.13
18.3	.022	7.13	5.4	.0255	8.36
16.0	.022	7.13	3.7	.0255	8.36
12.2	.022	7.13	2.0	.026	8.40

From the table it will be seen that the saturation point at which the measurements were started was about 33 per cent moisture content. As the sample dried out there was a gradual decrease in volume until about 18 per cent of water was reached when the contraction had amounted to 7.13 per cent of the original volume. From this point on there was very little, if any, contraction in volume over many per cent decrease in moisture content. When the soil reached about 6 per cent moisture content, however, a more rapid volume decrease commenced. At 2 per cent of water the volume decrease had reached

8.4 per cent of the original volume. These data are shown in another form in figure 11, where the moisture content is platted as abscissa and the per cent volume decrease as ordinate.

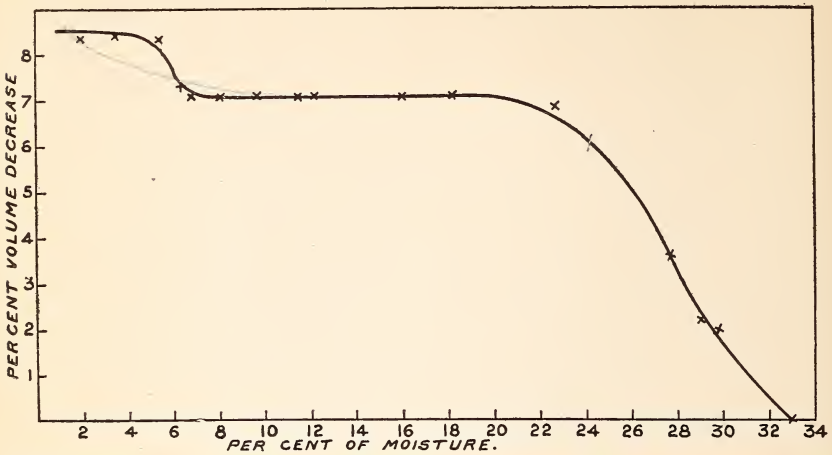

FIG. 11.—Volume-moisture results for Podunk fine sandy loam by the micrometer method.

In Table XIX and figure 12 is given a series of measurements made by the "glass-tube method," and these show the same variations as do the previous measurements.

TABLE XIX.—*Volume-moisture relations for Podunk fine sandy loam.*

[Length of soil column, 10 centimeters.]

Moisture.	Linear decrease.	Volume decrease.	Moisture.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
23.8	0.0	0.0	5.9	0.023	0.69
17.7	.015	.48	3.0	.043	1.30
9.3	.016	.50	1.6	.043	1.30
7.4	.016	.50			

The total percentage decreases are not the same by the two methods. As was pointed out in the chapter on penetration, the "absolute" values of these changes have no significance, but only the relation between the water content and the property being studied. It is to be noticed, however, that the measurements by the latter method were not begun at 33 per cent, but at 24 per cent, and if a similar range be taken on the curve of figure 11 the total volume changes by the two methods more nearly approach each other. Considering the curves

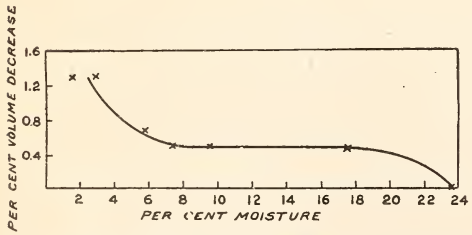

FIG. 12.—Volume-moisture results for Podunk fine sandy loam by the cathetometer method.

within the range of the moisture content covered in the penetration work—namely, 14 per cent to 0 per cent—it will be seen that from 14 to 6 or 7 per cent there is no appreciable change in volume in Podunk fine sandy loam, the loss of water over this range having no influence on the volume of the soil. In the neighborhood of 6 per cent, however, a change is noticeable, a loss of water beyond this point being accompanied by a diminution in the volume of the sample.

Thus, it follows that not only in the penetration but also in the aparent specific gravity a change occurs in the physical properties of the soil at about 6 per cent moisture content, which content is also the optimum. It is evident, therefore, that the optimum water content has an important physical significance and the work on volume contributes much to an understanding of the factors that operate at the optimum water content.

Results for Miami black clay loam.

Very satisfactory volume results were obtained in the measurements on the Miami black clay loam. The nature of the soil made it well suited to the soil column method of measuring volume change; because of its clayey nature and organic matter content it was able to retain the form of the soil column both in a very wet and a very dry condition. Further, the presence of the clay and organic matter caused greater volume changes, which added much to the ease of obtaining results.

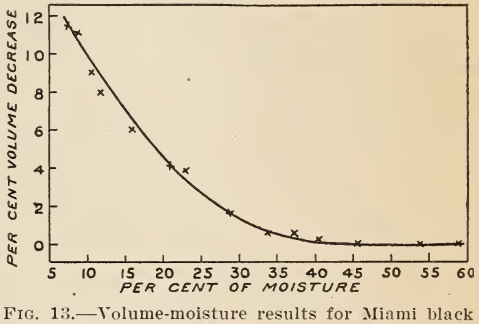

FIG. 13.—Volume-moisture results for Miami black clay loam by the soil column method.

A set of data obtained for Miami black clay loam on the volume changes with varying moisture content is given in Table XX and represented graphically in figure 13.

TABLE XX.—*Volume-moisture relations for Miami black clay loam by the soil column method.*

[Length of soil column, 14 centimeters.]

Moisture.	Linear decrease.	Volume decrease.	Moisture.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
59.0	0.0	0.0	20.9	0.195	4.1
54.0	.002	.0	16.2	.292	6.1
45.7	.002	.0	11.8	.383	8.0
40.4	.011	.2	10.8	.444	9.1
37.4	.022	.5	9.0	.537	11.1
34.0	.028	.6	7.6	.559	11.5
28.8	.078	1.6	6.7	.564	11.6
22.3	.181	3.9			

From this table it is seen that for moisture changes over a wide range near the saturation point there is no change in volume. At about 40 per cent, however, there begins a contraction in volume which continues down to the lowest limit to which the drying was carried. Another curve was obtained by the cathetometer method, the moisture content varying from the saturation point to well below the optimum. At the saturation end of the curve no variation in volume occurred, but at about 35 per cent moisture content a decided contraction began, which continued through the lower moisture contents. These data are given in Table XXI and figure 14.

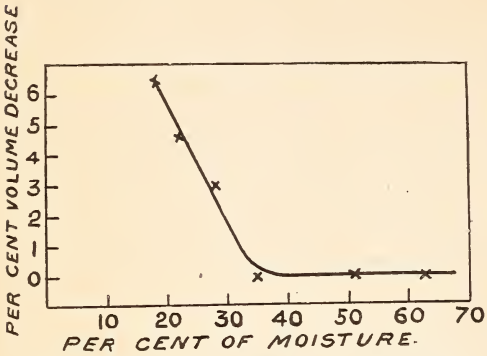

FIG. 14.—Volume-moisture results for Miami black clay loam by the cathetometer method.

TABLE XXI.—*Volume-moisture relations for Miami black clay loam by the cathetometer method.*

Moisture.	Linear decrease.	Volume change.	Moisture.	Linear decrease.	Volume change.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
61.2	0.0	0.0	28.2	0.04	3.1
51.8	.0	.0	22.6	.06	4.6
35.0	.0	.0	18.3	.08	6.5

Another set of results on the apparent specific gravity of the different samples is plotted in figure 15, from which it is seen that the results run parallel to the penetration data, as shown in figure 6. Thus, again the volume changes indicate that a change in the physical properties of the soil occurs in the region of the optimum water content.

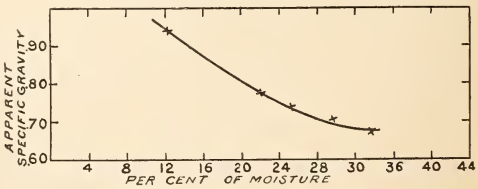

FIG. 15.—Apparent-specific-gravity-moisture results for Miami black clay loam.

Results for Leonardtown loam.

The data and curve for a set of measurements on the volume changes in Leonardtown loam are given in Table XXII and figure 16. This curve does not show a marked change in direction at 15 per cent moisture content, and has been added for the sake of completeness to illustrate what may be expected in volume meas-

urements on a soil of this nature. Numerous attempts to take measurements of the volume changes were made with this soil, from which widely varying results were obtained. A few of the forms of curves resulting from different methods are plotted in figure 17, and show that the behavior of this soil is quite irregular.

TABLE XXII.—*Volume-moisture relations for Leonardtown loam by the micrometer method.*

Moisture.	Linear decrease.	Volume decrease.	Moisture.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
33.0	0.0	0.0	22.6	0.194	6.35
32.4	.029	.96	20.6	.209	6.81
30.0	.097	3.19	17.3	.227	7.32
29.2	.119	3.86	15.9	.230	7.46
27.2	.147	4.79	14.7	.235	7.63
26.2	.166	5.38	12.6	.239	7.76
24.2	.176	5.77	11.7	.241	7.90
23.6	.185	6.03			

The variable conduct of this soil may be attributed to its uncertain plasticity, due to the irregular distribution of clay in the soil. As the soil dries out the particles stick together, and when dry the whole becomes cemented into a very hard and compact mass. This cementing of the particles interferes with whatever tendency the changing moisture condition might have to alter the internal arrangement of the soil.[a]

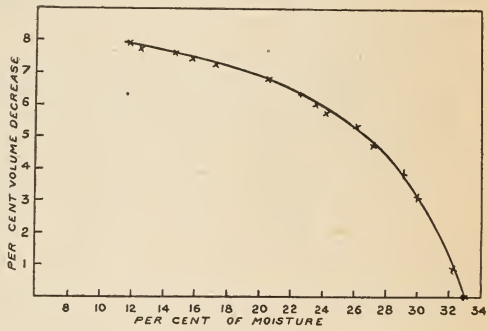

FIG. 16.—Volume-moisture results for Leonardtown loam by the micrometer method.

Upon examination of the curves in figure 2, in which are plotted the penetration results of Puchner, it will be seen that the measurements on clay samples show peculiarities very similar to those encountered in the present work. In the cases in which quartz and humus were in excess the penetration-moisture data all showed maxima in the curves. When kaolin was present in large amounts the penetration values increased steadily as the drying progressed, which action Puchner ascribed to the plastic nature of the material

[a] The subject of plasticity in clays has been discussed by many writers, and references to a few of the more important treatises are here given: Schlösing, Compt. rend., **74**, 1408 (1872); **78**, 1276 (1874); Jour. de l'agriculture, **9** iv, 50, 93, 140, 171 (1874) Hilgard, Forsch. auf dem Geb. Agr.-Phys., **2**, 441 (1879); van Bemmelen, Landw. Vers.-Stat., **35**, 69 (1888); Whitney, Bul. No. 4, Weather Bureau, U. S. Dept. Agr. (1892), p. 27; Ries Clays; Their Occurrence, Properties, and Uses. New York, 1906.

and to the hard, cemented character which the soil assumed on drying out. It is evident from the penetration results for Leonardtown loam that when the sample is worked up into condition at the different moisture contents, the cementing action accompanying drying out is largely prevented.

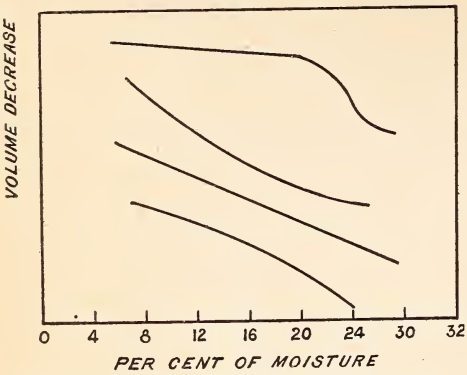

FIG. 17.—Volume-moisture results for Leonardtown loam by the soil column method.

The apparent specific gravity curve shown in figure 18 was plotted from the data contained in Table XXIII. A similar set of data is given in Table XXIV. In all cases there is a well-defined minimum at 15 per cent moisture content.

TABLE XXIII.—*Relations between penetration, apparent specific gravity, and moisture for Leonardtown loam.*

Moisture, calculated on dry weight of soil.	Weight required for penetration.	Apparent specific gravity.	Moisture, calculated on dry weight of soil.	Weight required for penetration.	Apparent specific gravity.
Per cent.	*Grams.*		*Per cent.*	*Grams.*	
2.8	77	1.07	15.0	43	0.828
6.0	59	.980	15.3	46	.822
10.4	48	.865	17.9	46	.828
12.4	49	.841	20.5	69	.868

TABLE XXIV.—*Relations between penetration, apparent specific gravity, and moisture for Leonardtown loam.*

Moisture, calculated on dry weight of soil.	Weight required for penetration.	Apparent specific gravity.
Per cent.	*Grams.*	
1.8	50	1.01
5.6	40	.812
11.0	34	.695
14.1	34	.690
17.3	40	.723

Results for muck.

This soil proved to be well suited for measurements on volume change by the soil column method, not only because it retained its form on contraction without developing large cracks, but also because it gave fairly large volume changes. The results of the series of val-

ues obtained for volume change with varying amounts of water by the soil column method are given in Table XXV, and shown graphically in figure 19.

TABLE XXV.—*Volume-moisture relations for muck by the soil column method.*

Moisture content.	Linear decrease.	Volume decrease.	Moisture content.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
217.0	0.0	0.0	90.0	0.181	3.8
200.0	.004	.1	83.4	.214	4.46
154.0	.018	.33	67.0	.273	5.31
138.0	.052	1.03	51.1	.372	7.63

From the curve it will be seen that beginning at 217 per cent of moisture, which represents the saturation limit, there is very little

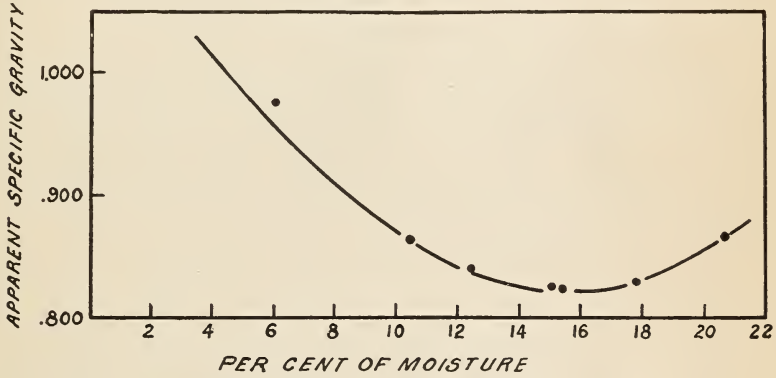

FIG. 18.—Apparent-specific-gravity-moisture results for Leonardtown loam.

decrease in volume over a wide range of moisture content. At 140 per cent of water there is a sharp contraction in the volume which continues down to 45 per cent, the air-dry condition.

A series of check results was obtained by the cathetometer method, and is given in Table XXVI and figure 20. The results are quite like those obtained by the column method, indicating that there is a large change between about 140 per cent of moisture and the air-dry condition. It follows that this soil exhibits the same critical changes in physical properties at the optimum water content as were found in the other soils.

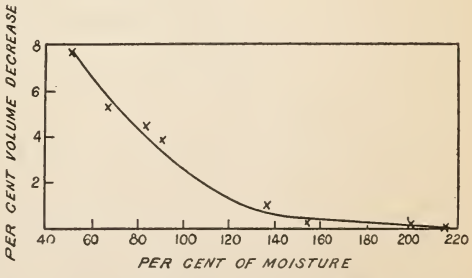

FIG. 19.—Volume-moisture results for Muck by the soil column method.

TABLE XXVI.—*Volume-moisture relations for muck by the cathetometer method.*

Moisture content.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*
210	0.0	0.0
185	.0	.0
164	.0	.0
120	.01	.76
84	.03	2.4

In figure 8 corresponding results for penetration and apparent specific gravity are given, the abscissas being common to both curves. It will be seen that the two curves are similar, indicating that it is possible to work this soil into the loosest condition at 120 per cent of moisture, at which point the soil is in the best possible agricultural condition. On the addition of water beyond this point the soil soon becomes too wet to be easily worked, as might be predicted from the rapid rise of the penetration curve.

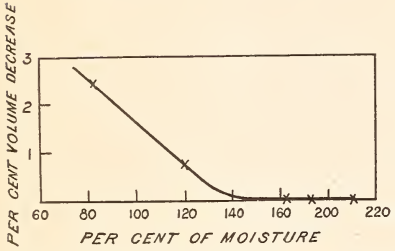

FIG. 20.—Volume-moisture results for Muck by the cathetometer method.

SUCCESSIVE WETTING AND DRYING.

Objects of experiments.

In studying the relation between volume change and moisture content one must consider what constitutes "natural" packing in the soil. It is known that there are large volume changes in soils under field conditions whenever the soil is dried or wetted. These volume changes render it highly improbable that the soil will stay in any condition of packing imposed by an external agency. It is a matter of common observation that when a soil is put into a loose condition by cultivation or other means and subsequently left undisturbed it will settle back in time nearly to its original volume. The relation between the change in volume due to settling and the change in volume due to a variation in moisture content was therefore investigated.

Experimental methods.

The methods of measuring the volume changes were the same as in the volume work described above. When the soil had gone through the process of drying out once it was wetted by capillary rise without in any other way disturbing it. A complete record of the volume measurements was obtained while the soil was drying out; the total change in volume due to wetting was observed without obtaining measurements for the intermediate moisture contents. This cycle could be repeated any number of times, and the variation in soil volume due to continued wetting and drying could be readily followed.

Results for Miami black clay loam.

The results of a set of measurements by the soil-column method for Miami black clay loam in which the original sample was in fairly loose condition are given in Table XXVII. For each cycle the volume decrease has been given in cubic centimeters and in per cent. In the last column is given the total volume decrease referred to the original volume. The separate curves are referred to the same standard for comparison, i. e., the original volume of the sample.

TABLE XXVII.—*Volume changes for the continued wetting and drying of a loose sample of Miami black loam. (Soil column method.)*

Cycle.	Moisture content.	Length of column.	Changes during separate dryings.		Total changes from original condition.	
			Linear decrease.	Volume decrease.	Linear decrease.	Volume decrease.
	Per cent.	*Centimeters.*	*Centimeter.*	*Cubic centimeters.*	*Centimeters.*	*Cubic centimeters.*
1	53.2	13.989	0.0	0.0	0.0	0.0
	41.1	13.989	.011	.2	.011	.2
	38.5	13.936	.064	1.3	.064	1.3
	25.2	13.904	.196	4.1	.196	4.1
	19.2	13.545	.455	9.3	.455	9.3
	9.5	13.366	.634	12.9	.634	12.9
	5.7	13.316	.684	14.0	.684	14.0
2	59.0	13.536	.0	.0	.464	9.8
	54.0	13.534	.002	.0	.466	9.8
	45.7	13.534	.002	.0	.466	9.8
	40.4	13.525	.011	.2	.475	10.0
	37.4	13.514	.022	.5	.486	10.3
	34.0	13.508	.028	.6	.492	10.4
	28.8	13.458	.078	1.6	.542	11.4
	22.3	13.455	.181	3.9	.645	13.7
	20.9	13.341	.195	4.1	.659	13.9
	16.2	13.244	.292	6.1	.756	15.9
	11.8	13.153	.383	8.0	.847	17.8
	10.8	13.092	.444	9.1	.908	18.9
	9.0	12.999	.537	11.1	1.001	20.9
	7.6	12.977	.559	11.5	1.023	21.3
	6.7	12.972	.564	11.6	1.028	21.4
3	58.3	13.469	0.0	0.0	0.531	10.5
	55.6	13.428	.041	.9	.572	11.4
	51.4	13.407	.062	1.3	.593	11.8
	37.2	13.373	.096	2.1	.627	12.6
	31.8	13.318	.151	3.2	.684	13.7
	22.1	13.195	.274	5.8	.805	16.3
	19.8	13.131	.338	7.2	.869	17.7
	15.5	13.000	.469	9.7	1.000	20.2
	12.3	12.858	.611	12.5	1.142	23.0
	9.4	12.809	.660	13.5	1.191	24.0
	7.8	12.793	.676	13.8	1.207	24.3
4	59.5	13.282	.0	.0	.718	14.6
	54.5	13.271	− .011	− .08	.729	14.5
	40.0	13.153	+ .029	+ .6	.747	15.2
	32.4	13.114	.068	1.4	.786	16.0
	21.0	13.107	.175	3.7	.893	18.3
	19.3	13.092	.190	4.0	.908	18.6
	14.9	13.027	.255	5.3	.973	19.9
5	56.0	13.218	.0	.0	.782	15.9
	34.8	13.151	.067	1.4	.859	17.3
	2.9	13.071	.147	3.1	.929	19.0

From the data for total volume change it can be seen that there is a decrease in volume on drying out the wet sample. When the dry soil is wet again, there is an expansion, which is not, however, as large as the previous contraction, so that the total effect for the cycle has been to reduce the volume of the sample. The effect of continually wetting and drying a loose sample of soil is better seen from the curves in figure 21, which have been plotted from the data given in the above table.

The volume decrease for the loose soil in drying from a saturated to an air-dry condition was about 14 per cent of the original. This change is represented by curve 1. On again wetting the dry soil, it still showed a volume of 10 per cent less than the original. If on drying out the second time the moisture content had been reduced as low as it was in the case of curve 1, the volume change would have been about 12 per cent. This can be seen by exterpolating curve 2 to a 5 per cent moisture content.

The volume change from the original condition is about 23 per cent; hence at the end of this drying the soil occupies 77 per cent of its original volume. Likewise when this dry sample was wetted again, the expansion was less than the previous contraction, so that at the end of the second cycle the sample was packed still more. The difference, however, between states 3 and 2 is much less than between 2 and 1. The volume occupied by the soil after the third wetting decreased 13.8 per cent on drying out, which indicates that, although the sample

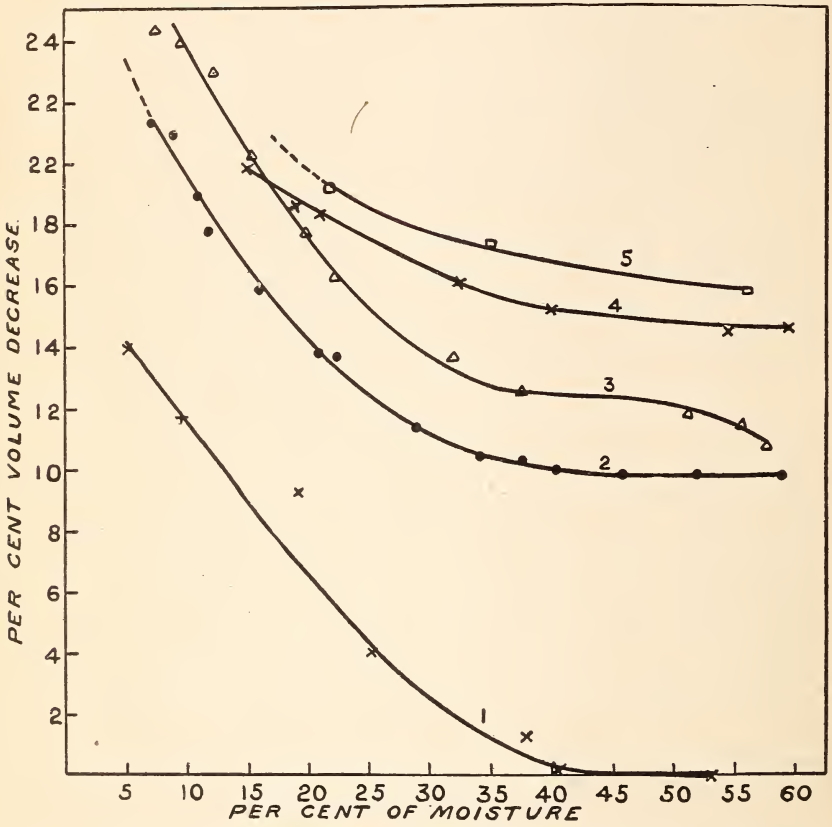

FIG. 21.—Volume changes with successive wetting and drying of loosely packed Miami black clay loam.

is packed more tightly, the contraction in passing from a saturated to an air-dry condition remains about the same. The results for the fourth and fifth dryings are represented by curves 4 and 5, and in general indicate that the changes due to successive wettings and dryings are more nearly identical and that the sample is approaching a condition of "natural" packing.

By the time curves 4 and 5 were obtained the soil column was in rather poor condition, owing to the fact that the cracks which formed

on drying were not repaired in the subsequent wetting, so that the soil column developed points of weakness which interfered with the measurements of the total volume changes. For a continued series of this kind the soil column method would not prove so satisfactory as a method in which the sample is contained in a dish and the height of the soil surface measured. The former method has, however, the distinct advantage of being rapid, since the surface exposed per gram of soil is relatively very much greater than if the sample were contained in a cup. It is probable that the first three curves are more reliable than those obtained when the soil column was weakened by cracks.

These measurements on the continuous contraction of a loose sample of Miami black clay loam lead to the following conclusions:

(1) On drying and wetting a loose sample of soil there is a marked hysteresis effect in the volume changes, resulting in a total contraction in volume for a moisture-change cycle.

(2) On successive wettings and dryings this hysteresis becomes less and less. When it disappears altogether, the expansion on wetting will be equal to the contraction on drying and a condition will have been attained which may be designated a "natural" packing of the soil.

(3) Curves 1, 2, and 3 show that within limits the contraction in drying from a saturated to an air-dry condition is not greatly dependent on the packing.

Results for Muck.

A sample of Muck in a loose condition was found to give similar results for successive wettings and dryings. The contraction on drying out the sample the first time was 29.2 per cent of the original volume. On wetting it increased, however, only 7 per cent; as the result, therefore, of one cycle the volume was 22.2 per cent less than originally. On drying out the second time the volume decrease was 7.6 per cent, which made a total volume decrease of 29.8 per cent.

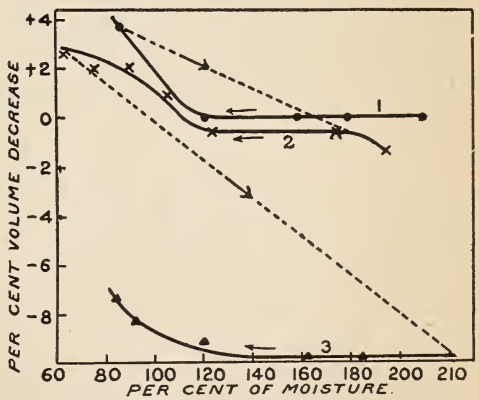

FIG. 22.—Volume changes with successive wetting and drying of closely packed Muck.

That the condition of natural packing in a soil does not represent the closest possible packing is evident from observations made on the successive wetting and drying of a very tightly packed sample of Muck. The soil, in a moderately moist condition, was closely packed into a cup and the change in volume with moisture content was fol-

lowed by the cathetometer method. The results stated in Table XXVIII are expressed in the same manner as in Table XXVII, except that when the volume of the sample becomes greater than in the original condition the total per cent decrease in volume is assigned a negative value. The original saturated condition is taken as zero on the percentage volume change scale, and increases and decreases in volume are figured down and up respectively from this point. The results are more easily appreciated from the corresponding curves in figure 22. The curves have been numbered in the order of the successive dryings. On drying out the original sample the usual volume contraction is noted. The direction of the change (not the actual path) on wetting is indicated by the arrows on the dotted lines. In this case the expansion on wetting was greater than the previous contraction, and at the end of cycle 2 the sample is in looser condition and occupies a greater volume than at the end of cycle 1. Curve 2 again shows a contraction on drying and a much greater expansion on wetting. Curve 3 also shows the usual contraction on drying.

TABLE XXVIII.—*Volume changes for the continued wetting and drying of a closely packed sample of Muck (cathetometer method).*

Cycle.	Moisture content.	Linear decrease.	Volume decrease.	Difference in volume.	Total volume decrease.
	Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Per cent.*
1	205.0	0.0	0.0	0.0	0.0
	179.0	.0	.0	.0	.0
	158.0	.0	.0	.0	.0
	120.0	.0	.0	.0	.0
	86.0	.05	3.98	.0	3.98
2	195.0	.0	.0	−1.32	−1.32
	175.0	.01	.76	.0	− .56
	123.0	.01	.76	.0	− .56
	105.0	.03	2.39	.0	+1.05
	92.5	.04	3.13	.0	+2.08
	75.0	.04	3.13	.0	+2.08
	64.0	.05	3.98	.0	+2.66
3	210.0	.0	.0	−9.8	−9.80
	185.0	.0	.0	.0	−9.80
	164.0	.0	.0	.0	−9.80
	120.0	.01	.76	.0	−9.04
	92.0	.02	1.58	.0	−8.22
	84.0	.03	2.39	.0	−7.41

In comparing this with the curves representing the continuous changes in a loose sample (fig. 25) the effect of continued wetting and drying is seen to be in an opposite direction. It is possible therefore to pack a soil so tightly that on continuous moisture changes the volume will increase. This hysteresis effect will cease when the expansion due to complete wetting just equals the contraction due to drying out to the air-dry condition, and the soil will then be in the state of natural packing. It has been suggested that within narrow

limits the change in volume on contraction was not greatly dependent on the packing. If this were not the case the influence of packing would have to be considered in measurements, such as were made by Wollny and others, on the "total" volume change due to wetting and drying. It has been made clear that unless the condition of natural packing is realized the volume decrease in drying will not be the same as the increase in the subsequent wetting. That the volume changes obtained by previous investigators (see Tables XIV and XV) on wetting a soil were different from those obtained for the same soil on drying was no doubt due to the fact that the samples were not in the condition of natural packing and that the hysteresis effects described above were encountered.

RATE OF EVAPORATION.

RELATION OF RATE OF EVAPORATION TO MOISTURE CONTENT.

Experimental methods.

Since vapor pressure, and hence rate of evaporation, varies with temperature, reliable results could be obtained only when the measurements were made at constant temperature. A large air thermostat was made for this purpose. In order to cut down radiation the walls were built double. The heating was done by electric lamps controlled by the Geer[a] form of electric thermo-regulator. The air was thoroughly stirred by means of a fan, driven from the outside by a motor. By means of this device the temperature could be maintained constant within 0.1° C. In order that the humidity might remain constant during evaporation the samples were put in desiccators over a relatively large surface of 95 per cent sulphuric acid, which maintained a partial vapor pressure of 0.1 millimeter mercury at 25° C., the temperature of the thermostat.

Thus by regulating the temperature and consequently the vapor pressure the conditions for evaporation were controlled satisfactorily.[b]

The method consisted of wetting to its saturation point an amount of soil equivalent to 20 grams of dry material. The weight of the bottle and soil was determined initially and at frequent intervals during the process of drying out in the desiccator. From the loss in weight and the time between successive weighings the rate of evaporation was calculated. From the observed weight of the soil and bottle and the dry weight equivalent of the soil, the moisture content at the time of weighing was calculated. The calculated rate of evaporation was based on the mean water content prevailing over the time in which the loss was occurring, i. e., the mean of the moisture contents calculated from two successive weights.

---

[a] Jour. Phys. Chem., 6, 85 (1902).

[b] Under these conditions the rate of evaporation from a dish of water should of course be constant. This was tried experimentally with satisfactory results.

Results for Podunk fine sandy loam.

A series of measurements on the rate of evaporation for Podunk

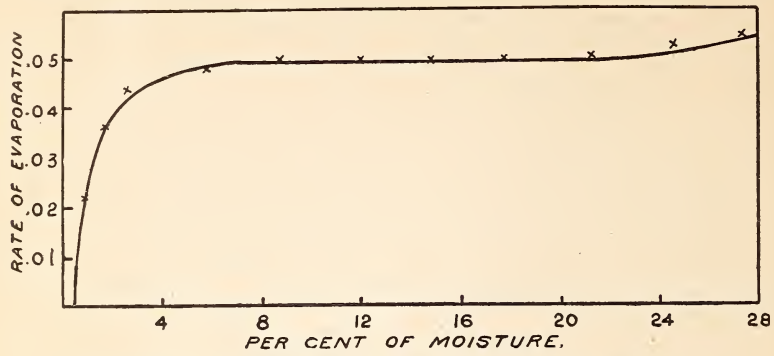

FIG. 23.—Rate-of-evaporation-moisture results for Podunk fine sandy loam.

fine sandy loam is given in Table XXIX, and is represented graphically in figure 23.

TABLE XXIX.—*Rate of evaporation from Podunk fine sandy loam over 95 per cent sulphuric acid at 25° C.*

Mean moisture content.	Time interval.	Loss.	Loss per hour.	Mean moisture content.	Time interval.	Loss.	Loss per hour.
Per cent.	*Hours.*	*Gram.*	*Gram.*	*Per cent.*	*Hours.*	*Gram.*	*Gram.*
27.4	19.5	1.0450	0.0536	8.7	14.5	0.7140	0.0492
24.2	4.5	.2362	.0525	5.8	9.9	.4712	.0476
21.3	18.7	.9210	.0493	2.4	4.0	.1732	.0433
17.8	9.3	.4595	.0494	1.7	2.0	.0719	.0359
14.8	15.3	.7495	.0490	.9	11.0	.2445	.0222
12.0	9.9	.4854	.0490	.3	2.0	.0097	.0049

The measurements on the rate of evaporation were begun when the soil held 28 per cent of water. The first evaporation was probably from the surface alone, so at first there is a small decrease in the rate as the water begins to evaporate from the pore spaces. Beginning at 22 per cent of water and extending over a wide range the rate of evaporation remains quite constant. At about 6 or 7 per cent a change takes place, for the rate decreases and continues to fall rapidly as the percentage of moisture decreases. Again, there is an obvious change in the physical properties of the soil at the optimum water content.

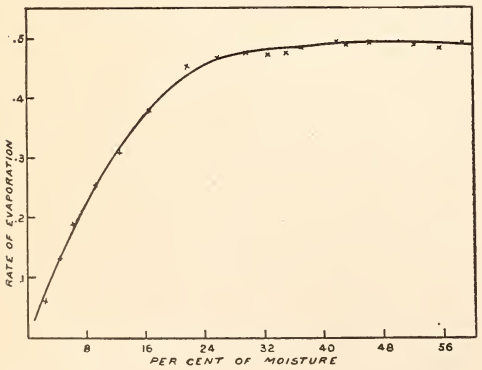

FIG. 24.—Rate-of-evaporation-moisture results for Miami black clay loam.

Results for Miami black clay loam.

On account of the high water content at the optimum in this soil the rate of evaporation method was exceptionally well suited to furnish a comparison of the soil condition at different water contents. The optimum for Podunk fine sandy loam lies so low that the change in the curve for the rate of evaporation might be supposed to be due to the relatively dry condition alone. In the present case the optimum lies about 30 per cent above the air-dry condition, so that changes in the character of the curve for rate of evaporation will be more significant. The data for this curve were obtained in the same way as for Podunk fine sandy loam. The data and the graphical representation are given in Table XXX and figure 24.

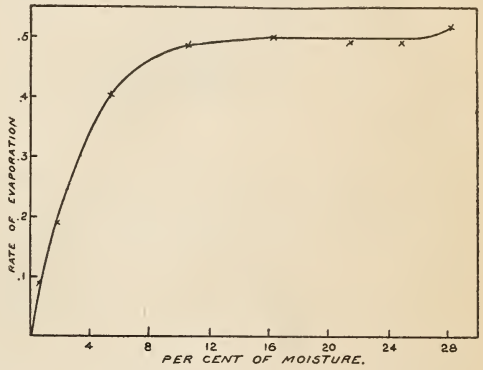

FIG. 25.—Rate-of-evaporation-moisture results for Leonardtown loam.

The evaporation curve which was started near 60 per cent is horizontal for about 20 per cent decrease in moisture content, showing a uniform rate above the optimum. At about 40 per cent, however, it gradually changes direction, the rate of evaporation falling.

TABLE XXX.—*Rate of evaporation from Miami black clay loam over 95 per cent sulphuric acid at 25° C.*

Mean moisture content.	Time interval.	Loss.	Loss per hour.	Mean moisture content.	Time interval.	Loss.	Loss per hour.
Per cent.	*Hours.*	*Gram.*	*Gram.*	*Per cent.*	*Hours.*	*Gram.*	*Gram.*
58.5	16.7	0.8198	0.0491	29.7	7.0	0.3321	0.0474
55.4	9.3	.4474	.0481	26.9	17.0	.7964	.0468
52.4	15.17	.7422	.0489	22.1	24.0	1.0879	.0453
49.4	9.9	.4802	.0485	17.1	24.0	.9109	.0379
46.4	14.5	.7155	.0493	12.9	26.25	.8108	.0309
43.4	9.9	.4808	.0486	9.5	22.25	.5716	.0257
41.0	11.0	.5427	.0492	6.7	24.5	.4694	.0192
37.5	11.0	.5411	.0483	5.1	22.75	.3056	.0134
35.4	6.5	.3099	.0477	3.7	23.75	.2136	.0090
32.6	17.5	.8295	.0474	2.7	24.25	.1470	.0061

For Miami black clay loam the studies in penetration, apparent specific gravity, and rate of evaporation all indicate that the critical moisture content which determines the physical properties of this soil lies between 35 and 40 per cent, which also is the optimum water content of the soil.

Results for Leonardtown loam.

The measurements of rate of evaporation from Leonardtown loam are given in Table XXXI and figure 25.

It has been shown that for this type of soil the volume relations at the optimum water content do not permit of very satisfactory conclusions. However, the penetration and evaporation measurements show critical changes at about 15 per cent of water, the optimum water content of the soil.

TABLE XXXI.—*Rate of evaporation from Leonardtown loam over 95 per cent sulphuric acid at 25° C.*

Mean moisture content.	Time interval.	Loss.	Loss per hour.	Mean moisture content.	Time interval.	Loss.	Loss per hour.
Per cent.	*Hours.*	*Gram.*	*Gram.*	*Per cent.*	*Hours.*	*Gram.*	*Gram.*
28.2	19.0	0.9770	0.0517	10.7	24.5	1.1963	0.0488
24.9	7.25	.3555	.0490	5.5	22.75	.9193	.0404
21.6	19.25	.9538	.0495	2.0	24.25	.4560	.0188
16.4	22.0	1.0962	.0498	.7	24.16	.0904	.0037

Results for muck.

The results for this soil are given in Table XXXII, and have been plotted in figure 26. When the soil in a very wet condition was put

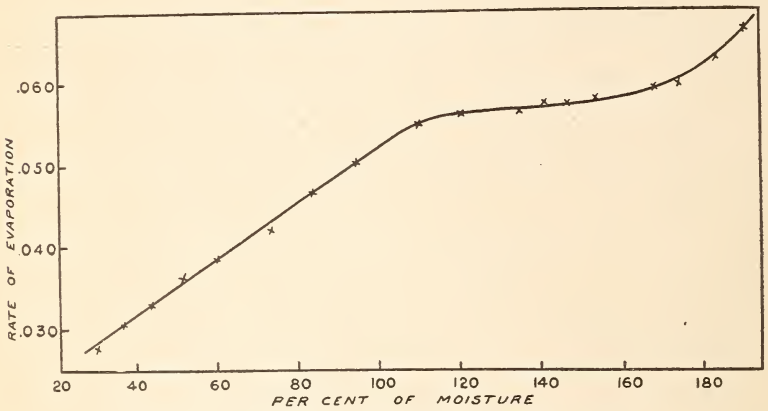

FIG. 26.—Rate-of-evaporation-moisture results for Muck.

over sulphuric acid in a desiccator there was at first a rapid drop in the rate of evaporation corresponding to the decrease as in the previous cases studied. The curves, however, indicate that for a wide change in moisture content it exhibits very little change in the rate of evaporation. At about 120 per cent there is a rapid decrease in the rate of evaporation, indicating that the critical moisture content has been reached. This decrease continues down to 30 per cent, at which point measurements were discontinued.

TABLE XXXII.—*Rate of evaporation from muck over 95 per cent sulphuric acid at 25° C.*

Mean moisture content.	Time interval.	Loss.	Loss per hour.	Mean moisture content.	Time interval.	Loss.	Loss per hour.
Per cent.	*Hours.*	*Gram.*	*Gram.*	*Per cent.*	*Hours.*	*Grams.*	*Gram.*
190	9.5	0.6362	0.0669	110	24.0	1.3233	0.0551
183	15.2	.9590	.0632	95	24.0	1.2120	.0505
174	9.85	.5905	.0600	84	26.3	1.2332	.0469
168	14.5	.8639	.0596	74	22.1	.9329	.0423
154	10.0	.5813	.0581	60	24.3	.9388	.0387
147	13.0	.7474	.0575	52	23.0	.8352	.0363
141	6.5	.3744	.0576	44	24.0	.7958	.0331
135	17.5	.9893	.0566	37	24.0	.7372	.0307
121	17.0	.9591	.0564	30	24.5	.6851	.0279

MOISTURE DISTRIBUTION.

MOISTURE FILMS.

When to a dry soil a very small amount of water is added by putting the sample in an atmosphere saturated with vapor, there will be a direct condensation on the soil grains, and water will be held partly or entirely in thin films on the surface of the soil particles. Owing to an attraction between the particles and the water at the surface, this absorbed moisture is held with very great force, and the wetting of the soil grains is accompanied by an energy change of considerable magnitude. On wetting a mass of dry soil the formation of this film in the manner stated is accompanied by another effect due to the contact of soil grains. The films merge, so that a number of soil grains may be considered as being covered by one continuous film, and pulled together at the points of contact by the tension of the connecting film. Considering for the moment the formation of the films around the grains, it is evident that as more water is added to the soil and the films get thicker a point will be reached where the surface attraction of the soil particle is no longer strong enough to retain more water, since the surface force decreases rapidly as the distance from the surface increases.[a]

Before this point is reached, however, the thickness of the water films at the point of contact between the grains has been increasing owing to the film tension at the points of high curvature in the angles between the grains.[b] The thin, wedge-shaped angles between the grains will act then as capillary spaces and help to hold water. Since the surface films and capillary films merge, it is impossible to distinguish between them. The forces exerted by these films determine

[a] Bakker, Zeit. phys. Chem., 56, 95 (1906).
[b] Briggs, Bul. No. 10, Bureau of Soils, U. S. Dept. Agr. (1897).

the changes in the internal arrangement of the soil particles and the physical characteristics of the soil.

EFFECT OF MOISTURE DISTRIBUTION ON VOLUME CHANGES.

When a soil is saturated with water the pore spaces are filled. Assuming that these soil capillary tubes are continuous and of uniform diameter, the capillary force holding the water is equal to the pull in an ordinary capillary tube of a similar size. In comparison with the capillary spaces occurring at the contact of the soil grains, these tubes are large, so that the capillary force exerted by them is relatively small. Since the water in the large spaces is not held by great force, it will be the first to evaporate and will have but little effect in changing the arrangement of the grains. As evaporation proceeds a point will be reached where the water begins to evaporate from the fine capillary spaces, which include the angles between the soil grains. At this point the forces of film tension become more noticeable. As the water held between the soil grains diminishes and retreats farther and farther into the angles, the surface film stretches, increasing the film tension and pulling the soil grains inclosed by it still closer together, thus producing a contraction in the volume occupied by the soil. The point where the effective film forces are just sufficient to cause changes in the internal soil arrangement will be designated the "critical moisture content." As evaporation continues still further the surface films around the grains and the capillary wedges held between the grains become thinner. The surface film forces continue to increase; hence the volume should steadily decrease until the soil reaches an air-dry condition.

It is evident from the data given for the volume changes in Podunk fine sandy loam that the above consideration is substantiated by experimental facts, and even more strongly by the volume changes observed with the other soils. Take, for example, Podunk fine sandy loam with about 14 per cent of water. At this point the large pore spaces contain considerable water, and as the soil dries out this water will be the first to disappear. Since the large capillary tubes constitute a relatively large part of the soil space available for water, they will hold a considerable percentage of the water when the soil is saturated. This will be particularly true in this soil, a sand, where the single intergranular spaces are large, owing to the size of the soil particles. The withdrawal of water from the larger pore spaces will therefore cause a large decrease in the moisture content of the soil. When the moisture content of the soil is about 6 per cent, the critical water content is reached and a change in volume begins.

It will be remembered that for volume changes in Podunk fine sandy loam a large volume contraction occurred between 33 and 18 per cent of water, between which limits the soil is too wet to ascribe

the variation to the tension of the surface films. As the measurements were made on fairly loose samples of soil, it is quite possible that this volume change was caused simply by a gradual settling of the wet soil particles. When wet beyond a certain point a sand becomes incoherent. The soil aggregates seem to break down and the grains slip easily over one another, the excess of water acting as a lubricant and reducing the friction between the grains. It is possible that the volume changes occurring near the saturation point may also, in part, be due to a tendency of the free water to buoy up the soil grains and in this way decrease the packing of the grains by lowering the effective specific gravity of the individual grains. As the wet soil dries out, this tendency decreases and vanishes at a content of water a little below the saturation point.

The larger volume changes due to addition of water in clay soils is sometimes attributed to the presence of large amounts of colloidal material, which is supposed to imbibe the water and swell like starch grains. This view can easily be brought into agreement with the above theory of volume change. The question of absorption in a cell has been quite fully considered by Kauffler [a] and it has been shown by Patten[b] that absorption with imbibition can be considered as a special case under absorption. For our purpose, therefore, it makes no difference whether the volume change is due to action on the exterior surface of the particles or to imbibition accompanied by an increase in size of the particles. In the case of a peat soil, for example, it seems entirely reasonable that on account of the nature of the material a large change in volume is due to imbibition and swelling of the cells. There is no reason why a similar view should not be held for clay, although here it is quite possible to explain the phenomena without recourse to this idea. The volume changes in clay are very much greater than in sand. On account of the large difference in soil surface in a similar volume of the two classes, we would also expect the capillary and film effects in clay to be very much greater. The proportion of the relative areas exposed by equal volumes of very fine sand and of clay may be as great as 1 to 300, a difference which is quite sufficient to explain the large differences in volume changes in the two soils, on the basis of surface absorption and surface tension.

EFFECT OF MOISTURE DISTRIBUTION ON PENETRATION.

Having shown that volume changes in soils can be explained on the basis of the forces exerted by the capillary and surface films around the grains, and that the critical water content for volume-change and that for penetration are identical, it remains to be seen how the above considerations regarding the distribution of water in the soil explain the phenomena observed in the penetration experiments.

---

[a] Zeit. phys. Chem., **43**, 686 (1903).

[b] Trans. Am. Electrochem. Soc., 11 (1907).

Consider first the case of penetration under conditions of loose structure. The variations in the penetrability of the soil were attributed to the ability of the soil grains to arrange themselves into aggregates. In a dry soil the cohesion between the grains is that of one dry, solid body for another, and is readily seen to be small. The particles are thus quite free to move each other and tend to settle down into a compact condition. When a small amount of water is added to the soil, it gathers over the surface as films and settles into the angles between the soil grains. The cohesion of the soil particles increases and the action of surface tension promotes the formation of floccules and increases the possibility of building up the soil into a loose structure. As more water is added the thickness of the films and the amount of water held in the angles between the grains increase, the cohesion increases, and the soil responds better to cultivation. This effect reaches a maximum when the amount of water that can be held in this way reaches a maximum, and will be indicated by the fact that a minimum amount of force will be necessary to penetrate the soil sample. Since the loosely arranged soil grains in this condition occupy the smallest possible percentage of the total volume of the soil, the remainder of volume being taken up by air, the resistance to the introduction of a penetrating tool is a minimum at this point.

The further addition of water beyond the critical moisture content begins to fill up the larger pore spaces and to flood the soil. The soil aggregates begin to break down, thereby increasing the force necessary for penetration. This is shown by a gradual rise in the penetration curve beyond the minimum. Parallel results are, of course, indicated on the apparent specific gravity curves. The variations in penetration with moisture content is therefore related to differences in the distribution of water in the soil.

This same theory of soil moisture distribution accounts for the penetration results obtained by the Puchner method, where the critical water content for penetration was indicated by a maximum. As dry soil was packed into the containing vessel, the sample can be considered to represent a "single grain structure." The wetting of this dry sample must have been accompanied by an increase in volume, which caused an upward movement of the soil surface and a horizontal thrust upon the sides of the vessel. This acted as a packing force to the already close arrangement. The wetting of the soil also caused an increase in cohesion, as has been pointed out above. If the penetration measurements, therefore, had been made first on the dry sample and then on the sample corresponding to the maximum cohesion, there should be noted an increase in the penetration value. When a soil is saturated with water, the flotation effect tends to sus-

pend the particles and decrease the packing. The excess of water, which renders the soil incoherent, acts as a lubricant, and increases the ease with which the soil grains slide over each other. At saturation this effect is greatest, so that the resistance to penetration is least. As the percentage of water decreases, this effect decreases, and the penetration values rise as shown by the curves. When the water disappears from the larger pore spaces, the critical moisture content and the point of maximum cohesion is reached, at which point the packing effect due to wetting the soil in a confined space is still in force so that the penetration value is high. As the amount of water further decreases there is a decrease in volume due to drying as already shown and a corresponding diminution of this horizontal thrust on the walls of the dish which causes a decrease in the penetration value. Therefore for a soil sample treated in this way the maximum force required for penetration is necessary at the critical moisture content. In the case of Podunk fine sandy loam the occurrence of the critical point in the penetration-moisture relations in both methods of measurement at about 6 per cent of moisture is not a mere coincidence, but is due to the same fundamental forces exerted by a certain quantity of soil moisture in its distribution upon the soil particles.

The change in the physical properties of a soil may be referred to one particular percentage of water only in case the distribution of the water in the soil is entirely uniform, which condition of course does not occur ordinarily. The distribution of water is affected in some measure by the size of the grains, irregularities in packing, gravity, and other variables which can not be controlled. The condition which has been described as influencing the internal arrangement of the soil grains can not then be correctly ascribed to a single point in the moisture variation, but must be considered as operating over a more or less narrow range of moisture content and subject to slight variation from sample to sample of one soil. Also, the measurement of this range may give slightly different results, depending on the method used. From a theoretical point of view the variation in range due to differences in the conditions prevailing does not detract from the value of the results or of the conclusions reached, since the cause of this variation is clear.

EFFECT OF MOISTURE DISTRIBUTION ON RATE OF EVAPORATION.

A further confirmation of the view that the content of soil moisture determines the physical properties of the soil is furnished by the investigation on the rate of evaporation of soil water from soils containing different percentages of water. It has been pointed out that a great difference must exist between the forces with which the water

is held in the larger pore spaces and in the capillary angles between the grains. From this the conclusion follows that there must be a corresponding difference in the rate of evaporation.

As the water evaporates out of the larger pore spaces, the rate of evaporation will be determined by diffusion and by the forces of capillarity. Since a considerable quantity of the total soil water is held in the larger pore spaces and since the capillary pull in these spaces is not great in comparison with the forces exerted in the fine angles between the grains, the influence of capillarity upon evaporation from the large spaces will be relatively small. In relation to the rate of evaporation much of the intergranular space can be considered to be of the same order of magnitude, for which reason the rate of evaporation over a considerable range will not decrease very rapidly while the soil is drying out. As the evaporation continues the water held in these pores will disappear, and the soil water will be distributed almost entirely in the fine capillary angles between the soil grains and on the grains as films, where the greater capillarity holds it more strongly. Below this critical moisture content there will be a gradual falling off in the rate of evaporation, due to the increasing attractions between the water and the soil, causing a lowering of the vapor pressure of the absorbed films. Where the thickness of the film is such that the surface attraction just begins to cause a lowering in the vapor pressure of the film, the equilibrium point between the soil moisture and a saturated atmosphere of water vapor is reached, and in such an atmosphere no further evaporation of water from the soil grains takes place. In the open air, however, we are not dealing usually with a saturated atmosphere, and so evaporation will continue from the soil, but under constantly decreasing vapor pressure of the absorbed water, which in turn will cause a corresponding decrease in the rate of evaporation. When the vapor pressure of the soil films corresponds to the partial pressure of the moisture in the atmosphere, evaporation will cease, equilibrium having been reached between the vapor in the air and the film water.

Below the critical moisture content there will be a decrease in the rate of evaporation due, first, to slower diffusion of the water vapor from the finer capillary spaces, and, second, to an increase in the film tension accompanied by a decrease in the vapor pressure of the film water. These two effects merge gradually one into another, so that a smooth curve showing the decrease in evaporation is the result, the rapid decrease in evaporation beginning when the water in the larger pore spaces has nearly disappeared.

CRITICAL MOISTURE CONTENT AND MOISTURE EQUIVALENT.

That there is a connection between the critical moisture content and the distribution of soil moisture follows, also, from recent work

done in this Bureau.[a] By means of a centrifugal machine a wet soil sample was subjected to a force about 3,000 times that of gravity, which tended to throw the water from the soil. Even when subjected to such a force it was impossible to reduce the soil sample to an approximately dry condition; in fact, the resulting soil samples contained enough moisture to correspond to good field condition. It is evident from this that part of the water is held in the soil by very strong forces. The only moisture removed from the soil was that held in the larger pore spaces. When the moisture content of the soil is reduced to the point where the water is held in the form of films and as capillary water between the soil grains, it is retained more tenaciously. It was also pointed out that the amount of water removed from the soil is not directly proportional to the centrifugal force used; that is, the soil can be reduced from very wet to a medium condition by a relatively small force. If at this point the speed be doubled, which means that the centrifugal force will be quadrupled, the further reduction of moisture content is comparatively small. This is in agreement with the conclusions reached from the present studies on the rate of evaporation from soils. Instead of measuring the retentiveness of the soil in terms of centrifugal force, here the effect of such a retentiveness on the rate of evaporation has been measured. When the soil moisture is held in the larger pore spaces, the rate of evaporation is fairly constant and not very much less than would be obtained under similar conditions from a free water surface. In other words, the retentiveness of the soil is not very great as indicated by the rate at which that part of the soil moisture evaporates. However, when the critical moisture content is reached, the rate of evaporation immediately begins to decrease, indicating that the soil water is held by greater forces in the finer capillary spaces. As the water surfaces retreat farther into the angles between the grains and the films on the grains become thinner, the forces holding the soil moisture in place increase: this in turn produces a decrease in the rate of evaporation. The results obtained by the centrifugal method agree with the rate of evaporation results, indicating the point at which the larger soil forces come into play. To compare these two methods of studying the distribution of soil moisture one may use the measurements of Briggs and McLane on Norfolk fine sandy loam and the measurements above recorded on Podunk fine sandy loam. The Norfolk fine sandy loam very closely resembles the Podunk fine sandy loam in its physical characteristics. This similarity is shown in part by the comparison of the mechanical analyses of the two soils given in Table XXXII.

[a] Briggs and McLane, Bul. No. 45, Bureau of Soils, U. S. Dept. Agr. (1907).

TABLE XXXIII.—*Mechanical analyses of Podunk fine sandy loam and of Norfolk fine sandy loam.*

Soil.	Fine gravel, 1 to 2 millimeters.	Coarse sand, 1 to 0.5 millimeter.	Medium sand, 0.5 to 0.25 millimeter.	Fine sand, 0.25 to 0.1 millimeter.	Very fine sand, 0.1 to 0.05 millimeter.	Silt, 0.05 to 0.005 millimeter.	Clay, 0.005 to 0.0 millimeter.
Norfolk fine sandy loam	0	0.5	4.8	54.6	13.4	18.1	8.5
Podunk fine sandy loam	0	0	1.0	47.6	30.4	18.8	2.2

From this comparison it is seen that both soils contain a larger percentage of fine sand than of any other separate and that the quantities in the two soils are comparable. The Podunk soil contains somewhat more very fine sand than the Norfolk soil. The amount of silt is the same in both cases, but the amount of clay in the Podunk fine sandy loam is less than in the Norfolk fine sandy loam. By means of the centrifugal method the "moisture equivalent" was found to be 6.5 per cent of moisture. The critical condition of soil moisture for Podunk fine sandy loam, determined by the rate of evaporation method, was found to be 6 per cent, which is in agreement with the critical moisture value for this same soil as determined from the penetration and volume-change studies. The value obtained from the similar Norfolk fine sandy loam by the centrifugal method is just a little higher, which may easily be attributed to the higher clay content of that soil, since we know that the clay in a soil exerts a large influence on its water-holding power. As no determinations are available for the "moisture equivalent" of Muck or of the Miami black clay loam, there is no basis for comparison of these results. It is possible, however, to compare the sample of Leonardtown loam used in our investigations with a Hagerstown silt loam and a Clarksville silt loam, studied in the centrifugal work of Briggs and McLane.

A comparison of the mechanical composition of these three soils is given in Table XXXIV.

TABLE XXXIV.—*Mechanical analyses of Leonardtown loam, of Clarksville silt loam, and of Hagerstown silt loam.*

Soil.	Organic matter.	Gravel, 2 to 1 millimeters.	Coarse sand, 1 to 0.5 millimeter.	Medium sand, 0.5 to 0.25 millimeter.	Fine sand, 0.25 to 0.1 millimeter.	Very fine sand, 0.1 to 0.05 millimeter.	Silt, 0.05 to 0.005 millimeter.	Clay, 0.005 to 0.0 millimeter.
Leonardtown loam	.....	0.1	1.2	0.9	3.1	6.4	70.9	16.7
Clarksville silt loam	1.2	1.2	1.4	.9	2.0	5.6	73.2	14.8
Hagerstown silt loam	1.0	.3	.6	1.5	9.1	10.5	60.3	17.4

Clarksville silt loam more closely resembles the Leonardtown loam than does the Hagerstown silt loam. In all of these soils silt is in excess, varying from 60.3 to 73.2 per cent for the three soils. As

regards this point, the Leonardtown and the Clarksville soils are closely comparable. The clay contents are about the same, being slightly higher in the Hagerstown silt loam. The "critical moisture content" was found to be about 15 per cent for the Leonardtown loam. The "moisture equivalent," as determined by the centrifugal method, for the Clarksville soil was 15.1 and for the Hagerstown sample 16.5. From the close similarity in the mechanical composition and in the moisture values given, it would appear that the *critical moisture content* corresponds to the *moisture equivalent* as determined by the centrifugal method, as well as to the optimum water content, as determined by plant growth and cultural practices.

OPTIMUM WATER CONTENT AS REGARDS PLANT GROWTH.

The usual definition of optimum water content is that amount of water in the soil which is best suited to plant growth. But no emphasis has been placed on this during the course of the previous discussion, where it has been spoken of more often as the amount of water determining the best physical condition of the soil. It can be shown that the amount of water determining the best physical condition of the soil is generally the amount of water most favorable to plant growth. In this connection some evidence is given by Heinrich,[a] who determined the amount of water present in the soil when wilting of plants begins. In the six soils used determinations were made of the point of saturation, of the moisture content at which plants wilt, and also of the hygroscopic water content. This last was done by spreading the soil on a watch glass and exposing it for a week to an atmosphere saturated with water vapor. The results of this investigation are given in Table XXXV.

TABLE XXXV.—*Relation between hygroscopic moisture content and moisture content at which plants begin to wilt, according to Heinrich.*

Soil.	Water content at saturation.	Hygroscopic water content.	Moisture content at which plants begin to wilt.
	Per cent.	*Per cent.*	*Per cent.*
Coarse sand	26.5	0.42	1.5
Medium fertile garden soil	43.9	1.68	4.6
Infertile sandy muck	41.4	.97	6.2
Sandy loam	43.3	2.40	7.8
Very fertile calcareous soil	38.3	3.65	9.8
Peat soil	274.0	20.6	49.7

From this table it is evident that hygroscopic water is not sufficient to supply the needs of a plant, but it indicates also that the plant can exist on a relatively small amount of water. In comparison with the moisture content at which wilting occurs, the amount pres-

[a] Zweiter Ber. Landw. Vers.-Stat. Rostock, 1894, 19.

ent in the soil at the critical moisture content is large indeed, and seems to be entirely sufficient for good plant growth. A possible objection is that the optimum water content is not the same for all plants, but from the above consideration it is evident that at the critical water content enough water is present for a good, if not an optimum, plant growth. In further experiments on two soils in continuation of the experiments just described the wilting points were determined for a large number of field crops. These results are given in Table XXXVI.

TABLE XXXVI.—*Moisture content at which wilting begins for two soils, according to Heinrich.*

Plant.	Moisture content at which plants begin to wilt.	
	On calcareous soil.	On peaty soil.
	Per cent.	*Per cent.*
Oats	8.4	3.23
Barley	9.98	33.3
Rye	9.55	32.8
Wheat	.....	43.6
Corn	7.91	.....
French rye grass (*Arrhenatherum elatius*)	.....	33.2
English rye grass	.....	33.1
Meadow foxtail	.....	34.2
Soft brome grass	.....	32.8
Red clover	10.28	34.3
Sweet clover	8.77	.....
Lambs clover	9.24	.....
Crimson clover	.....	34.1
Alfalfa	8.9	.....
Vetch	.....	35.3
Esparcet	9.92	.....
Fire bean	11.04	.....
Horse bean	11.30	.....
Potatoes	5.07	41.4

Considering the possible variations due to the difficulty of making close representative moisture determinations in soils and the experimental difficulty of correctly judging the time of wilting, there is a striking agreement in the above results for various plants. The average for the calcareous soil is about 9 per cent of water, from which figure there is no striking variation in any of the cases considered, and the average for the peat is about 34 per cent of water.

The general belief that different plants require different optimum water contents in the soil seems to be a result of observations on the total amount of water that the plant actually requires rather than on the percentage in the soil best suited to its needs. The transpiration in one plant may be greater than in another, and the corresponding demand for water would be greater. Investigators in this field have usually supplied the extra amount of water demanded for this larger transpiration by increasing the total water content of the soil rather than by supplying more water as it is needed. That is, instead of gradually supplying a larger amount of water and maintaining the

moisture content of the soil near a constant percentage, the same result is obtained by increasing the percentage of water in the soil at one time. The idea that there are different optimum water contents for the same soil for different plants may, therefore, be an outgrowth of the prevailing methods rather than of critical experimentation. Moreover, the idea that there are different optimum water contents corresponding to different plants has apparently been confused with the fact that some plants have more endurance under adverse moisture conditions than have others. These same plants may be able to grow in a large excess of water without great apparent injury, but actually require less for more favorable growth. The fact that one plant can tolerate larger amounts of water than another without serious injury does not alone justify the conclusion that the optimum water content differs for each.

From this work, showing the moisture content approximately constant with any one soil at which wilting of different plants begins and from the other considerations presented, it seems probable that the optimum water content is that which makes for the greatest aeration, loosest structure, and, in general, most favorable physical condition of the soil.

APPARATUS AND METHODS.

SCREENING APPARATUS.

In beginning work on penetration of soils in the loose condition, it was recognized that there existed a serious difficulty in obtaining a uniform packing and so arranging the conditions that the same grade of packing could be obtained on successive trials, thus insuring duplicate results. A preliminary investigation was made on the effect of packing on penetration. The firmness of the packing was determined from the weight of the soil, since the measurements were all made under one moisture condition and the soil was leveled in such a way that the same volume was always obtained. The change in packing was effected by jarring the dishes and by varying the method in which the soil was put into the containing vessel. The results of such a series of measurements on Leonardtown loam containing 9.1 per cent of water are given in Table XXXVII.

TABLE XXXVII.—*Influence of packing on penetration.*

Weight required for penetration.	Weight of soil.
Grams.	*Grams.*
70	1,785
75	1,808
85	1,830
113	1,902
175	1,965

When these results are plotted, using the weights of the soils as abscissas and the weights for penetration as ordinates, a smooth curve is obtained, showing that the penetration is not in direct proportion to the weight, but increases more rapidly. But for a small variation in packing, such as would be met under ordinary experimental conditions, the penetration is, for all practical purposes, a linear function of the packing. This is confirmed by the following measurements made on Leonardtown loam, which held about 15 per cent of water, its optimum water content.

TABLE XXXVIII.—*Influence of packing on penetration.*

Weight required for penetration.	Weight of soil.
Grams.	*Grams.*
64	1,702
71	1,719
87	1,739

These results when plotted lie on a straight line and indicate that soil variations or manipulations cause considerable differences in packing which, in turn, interfere with all measurements on penetration. The importance of having a satisfactory method of packing

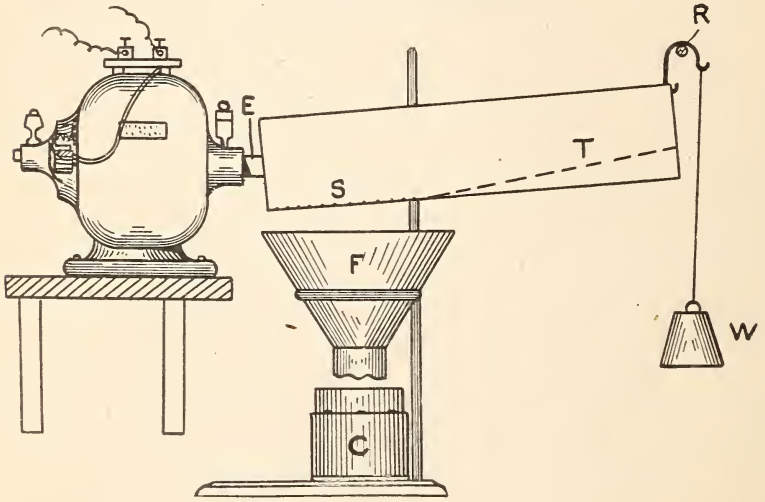

FIG. 27.—Apparatus for screening soils.

is therefore evident. Uniform packing is realized only when the process is entirely mechanical.

The apparatus finally used is shown in figure 27. To the shaft of an electric motor is fastened an eccentric *E*, made from a rod 2 centimeters in diameter, in which the shaft hole is drilled 0.5 centimeter off center. This eccentric fits into a hole in one end of the

screen box *ST*. The motion of the revolving eccentric gives the screen a rapid shaking in both vertical and horizontal planes, which is very effective in forcing the damp soils through the mesh. The screen *S*, which is of 3 meshes to the centimeter, is in only one end of the box. A false bottom *T*, made of tin, serves to feed the material toward the mesh during shaking. The upper end of the box is supported by means of two hooks, resting on a horizontal rod *R*, shown in cross section in the figure. The hooks are made of heavy insulated electric-light wire, the covering of which serves to reduce the noise caused by rattling. Further, to prevent rattling at that end of the screen, a kilogram weight *W* is hung between the hooks. With this method of support the upper end of the screen is free to move, yet the motion is so reduced that during shaking the box stays well in position. The soil, after passing through the screen, falls into a funnel *F* and from there into the cup *C*, which holds the sample during the remainder of the experiment.

The cup proper is 12.5 centimeters in diameter and 9 centimeters high, having a capacity of 1,100 cubic centimeters. A rim is added, which makes it possible to fill the cup above its own level. The rim is then removed and the soil leveled off to the edge of the cup. This gives a more uniform packing in the upper layer of the soil.

The shaker makes it possible to repeat the packing of the same sample and also gives a basis of comparison in the measurements made on different samples, since the soil in each case is treated in the same way, falls through the same distance, and therefore is subjected to the same packing forces. Reproduction of these conditions is essential in a series of measurements made upon samples containing different quantities of water, where it is desirable that the only variable entering should be the water content.

PACKING APPARATUS.

The soil sample packed by the method just described is put into a uniform condition for experiment. Starting with the soil sample thus prepared it is possible to vary the packing in a definite and known way and thus study the effect of packing on the physical condition of the soil. The packing is done by the arrangement shown in figure 28, where a front and side elevation of the apparatus is shown. A vertical shaft of brass *AB* works easily through a wooden guide block *G*. On the bottom of the shaft is a circular plate *B* of hard rubber, just a little smaller than the inside of the cup *C*, into which it fits when packing the soil. On the upper end of the shaft is another plate *A*, which serves as a scale pan for the weights *W*, which are of lead and so made that they can be placed in the middle of *A* and

concentric with one another, thus avoiding any serious side thrust where the rod passes through the guide. The shaft and plates are connected over pulleys with a weight L, by which they are balanced. In order to have the cup C still full after packing, a rim R, 4 centimeters high, is put on the cup. The screened soil is leveled to the upper edge of R and packed under any desired weight at a steady pressure for four minutes, after which the rim is removed and the soil surface reduced to the level of the cup proper. The sample is then ready for the penetration tests.

The behavior of the soil when packed in this way is indicated in figure 29, where a series of measurements for Podunk fine sandy loam

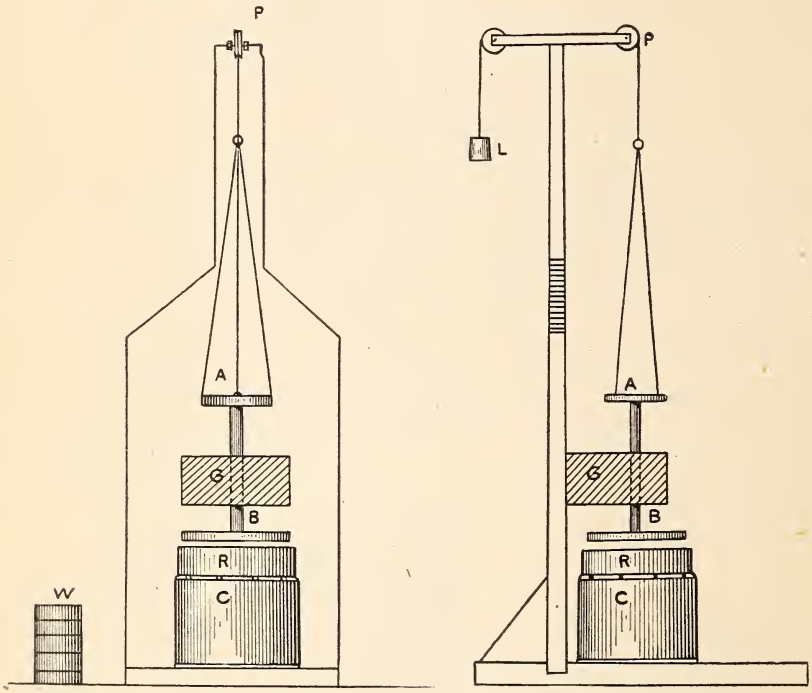

FIG. 28.—Apparatus for packing soils.

containing 2.3 per cent water is shown. In addition to the packing caused by the soil falling from the screening machine, the soil was further compressed under pressure of 10, 30, and 50 grams per square centimeter. These pressures correspond to weights of 1, 3, and 5 kilos, the area of the compressing plate being about 100 square centimeters. The curve indicates that the increased packing pressure applied in this manner gives a fairly uniform increase in the force required for penetration.

PENETRATION APPARATUS.

The force required for penetration was measured on the apparatus shown in figure 30. The penetrating tool A is made from a steel rod 1 centimeter in diameter. This is turned into the form of a cone 10.5 centimeters long and 1 centimeter in diameter in the thickest part. The large end of this cone terminates in a tongue which is so fastened to the scale beam AB that it is free to swing in the vertical plane of the beam. The beam itself, made of oak, is 140 centimeters long from the end A to D, the point of rotation. A counterweight W balances the beam and its attachments. Midway between A and D a pail P is hung, into which sand is run from a funnel F through a rubber tube closed by a pinchcock. This gives a method of constantly adding weight without jarring and of increasing the pressure to just the value necessary to force the tool into the soil to the required depth. The scale beam is guided beteween the upright parallel rods G, spaced to allow a free movement of the beam between them. M_1 and M_2 are clamps that check the up-and-down movement of the beam. The depth to which the point penetrates is determined by the position of M_2. The measurement is always begun at the same height—the level of the cup, which was also the soil level—and weight is added until the beam reaches M_2, by which time the tool has penetrated 6 centimeters into the soil. The approach of the beam to M_2 is observed by means of a small mirror R fastened at an angle to M_2.

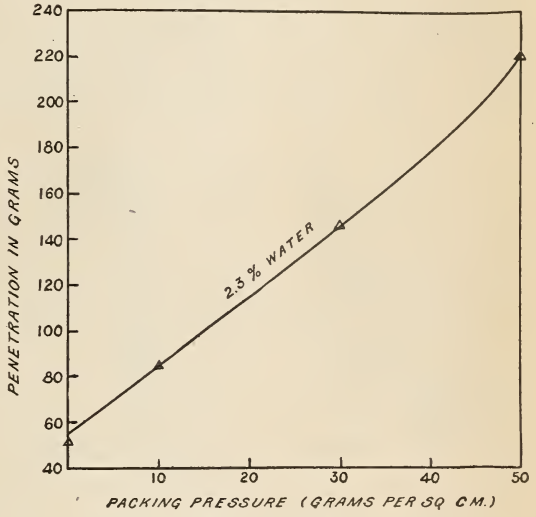

FIG. 29.—Penetration-packing results.

In making a penetration measurement the procedure is to make up a large soil sample to the desired water content, which is then determined accurately by drying a sample at 110° C. and calculating as per cent on the dry weight of soil. This method makes the different water contents of the same soil comparable one with another. The total sample is well mixed by screening and placed in a tightly covered pail. This holds enough soil to permit of repeating the measurements

several times without twice using the same portion of soil. This is essential because a wet soil dries out quite rapidly when exposed to the open air, particularly during screening. By using a fresh portion each time successive measurements are made there will be but slight differences in the water content of the different samples. The soil is then leveled to the top rim by cutting off the extra material in such a way that no packing results, after which it is pressed, if desired, in the packing machine, the rim removed, and the soil again cut off to the level of the top of the cup. The penetration measurements are then made; generally three trials for each sample. They should be made at points the same distance from the rim of the vessel and equal distances apart. This condition is easily attained by drawing on the table a circle the size of the cup and eccentric to the point of the penetrating tool. The cup is so placed that it always coincides with this circle and between each measurement is rotated through 120 degrees. This method of spacing eliminates the personal factor of

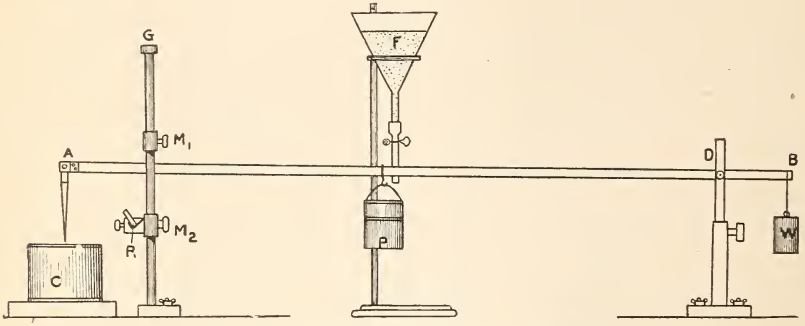

FIG. 30.—Apparatus for measuring penetration.

choosing the points for penetration and also makes the results more concordant. Since the soil in falling through the funnel of the shaking machine generally runs into the middle of the dish, from which point it spreads toward the sides, it tends to pack in the middle of the dish somewhat more closely than around the edges, so the packing at equal distances from the center is the same. After penetration the weight of the sand required to force the tool into the soil is determined. Since the pail is suspended in the middle of the beam, one-half the weight of the sand is the pressure applied in penetration. The cup and the soil are also weighed, the weight of the cup subtracted, and the specific gravity of the soil sample calculated from the volume of the cup.

No difficulty is experienced in taking three penetration measurements on one dishful of soil. The three points at which the penetration tool enters the soil are far enough apart that the crowding aside of the soil at one point by the penetrating tool does not affect

the following measurement at another point. Should it do so the force required for penetration would increase with each successive measurement, while as a matter of fact the variation is in no way regular between the different measurements.

APPARATUS FOR MEASURING VOLUME.

Preliminary method.

The first apparatus designed for volume measurements was not intended for very extended use, but rather as a convenient method of preliminary investigation. Some parts of it were used in subsequent investigations, and therefore a description of it is given here. The apparatus is illustrated in figure 31. The soil is contained in a glass tube *A*. For this purpose an Argand chimney has been found satisfactory and of suitable dimensions. In order to permit the wetting of the soil by capillarity the bottom of the tube *A* is closed by a ring *B*, made from a piece of brass tubing 2.5 centimeters long, with an inside diameter just a little larger than the outside diameter of the glass tube. A disk of brass gauze is soldered into the ring, as indicated in the diagram by the heavy dotted line. The ring is fastened to the tube by means of three set screws, one of which is indicated by *C*. In order to keep the finer soil particles from sifting through the brass gauze the end of the tube is covered by filter paper *D* before insertion into the ring. The dry soil is poured into the glass tube and then wetted by dipping the bottom of the container into water. Bearing on the upper surface of the soil is a brass tube *MN*, which works through a wooden guide block *E*. Changes in the volume of the soil cause, of course, a change in the level of the upper surface, and this change is communicated to the tube *MN*, and followed at *M* by a micrometer screw held firmly in place to the support of which *E* is a part. In order to hasten the drying the evaporation from the surface of the soil at *N* is increased by blowing a stream of air into the top of the tube. The air used for this purpose is passed through sulphuric acid in order to dry it. The drying progresses slowly owing to the small amount of surface exposed when *N* is in position. It is not feasible to remove *N* between measurements on account of the uncertainty of getting it back into the

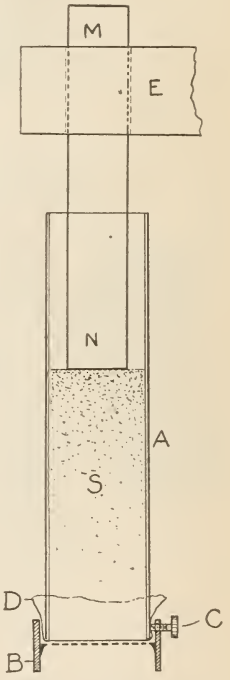

FIG. 31.—Apparatus for glass tube method of measuring changes in soil volumes.

same place when another measurement is to be made. As the drying occurs only at one end of the soil column an error is introduced, since the top of the soil was drier than the bottom. However, in a soil column of this length, if the drying proceeds slowly, this difference in moisture content of the top and the bottom is not very marked. More serious difficulty might be caused by the adhesion between the soil and surface of the glass, which would seriously cut down the influence of changing moisture content on the volume. It is evident from this preliminary attempt that a method suitable for accurate volume work should embody the following points: (1) In order to shorten the time required for carrying through one experiment it is essential that the drying out of the wet sample be rapid; this can be accom-

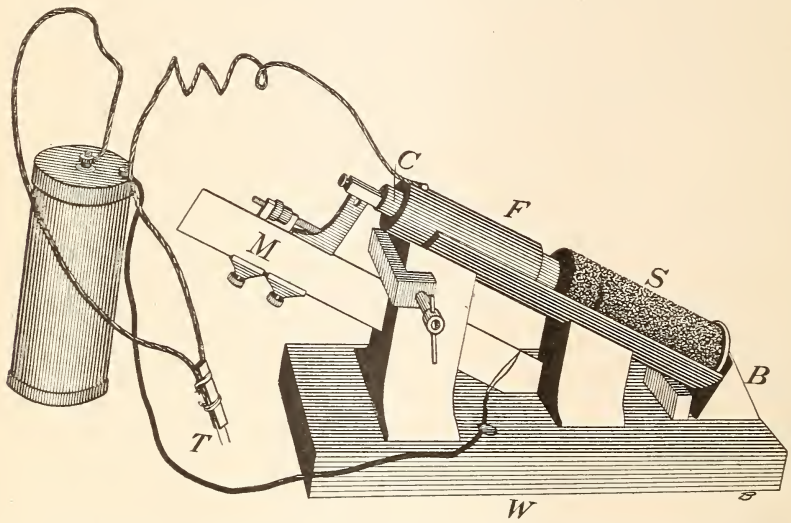

FIG. 32.—Apparatus for soil column method of measuring changes in soil volumes.

plished by exposing as great an area per unit volume of soil as possible. (2) The thickness of the soil from the drying surface down should be small in order that no large difference in moisture content may occur between the top and the bottom of the sample. (3) Since the change in volume is measured by the linear contraction it is essential to have the length in this one direction as great as possible. (4) The soil should be supported in such a way that after drying out it can be wetted again by capillarity without otherwise disturbing the sample, thus making it possible to use the same soil sample through several cycles of moisture change. (5) The soil sample should also be supported in such a way that it is independent of the measuring apparatus and movable at will, so that the same micrometer may be used to measure several samples drying out at the same time. These considerations led to the development of the "soil column method."

Soil column method.

The apparatus used in this method is shown in figure 32. The soil column *S* is molded in an apparatus similar to that shown in figure 31, where the soil is either put in dry and wetted by capillarity or packed into the tube in moderately moist condition, in which state it holds together well when pushed out of the tube onto the brass support shown in the figure. This support is made by cutting longitudinally a brass tube of a diameter a little larger than that of the soil column. Into one end of the support a circular brass disk is screwed so that it is perpendicular to the axis of the tube. Against this disk the lower end of the soil column rests. The disk is perforated so that a column can be wet by capillarity by simply dipping the lower end of its support into water, thus rewetting the sample without in any other way disturbing it. In this arrangement a large surface of soil is exposed to evaporation, and drying proceeds with considerable rapidity. A wet column of this kind reaches the air-dry condition in two to five days, depending on the nature of the soil. This method also insures a comparatively uniform moisture content from the top to the bottom of the sample. Resting against the upper end of the soil column is a brass follower *F* made from heavy brass tubing by inserting into the two ends pieces turned from solid brass. The part projecting from the lower end is made somewhat smaller than the tube so that it will not come in contact with the surface of the soil support, because upon contraction enough soil is left to roughen considerably this surface. The upper end contains a contact piece *C* turned from a brass rod. This is so arranged that by means of a screw, shown in the figure, it may be adjusted to lengthen or shorten the follower. By means of this adjustment the total length of the soil column and the follower can be made nearly the same in different samples, thus adapting the limits of the micrometer screw to their measurement. The Vernier scale and micrometer screw are shown at *M*. As the soil contracts during the wetting, the inclination of the support and the weight of the follower are sufficient to keep it pressed down against the end disk. The contraction of the soil therefore results in a downward movement, which is measured by the micrometer. In order to tell just when the micrometer comes in contact with the end of the follower at *C* an electrical contact device is used. One terminal of a battery is connected through an electric bell to *F*. When *M* makes the metallic connection at *C*, the circuit is closed and the bell rings. Instead of the bell the figure shows an arrangement *T* in which the two bare terminals are held at a short distance apart. By placing these two wires on the tongue, the instant of contact at *C* may be detected by a sharp acrid taste. This device is even more delicate and satisfactory than the bell. The contact can be

determined with such precision that the readings taken at the same time show no variation within the limits of the micrometer used. The micrometer scale is held firmly in place by means of a screw clamp. The wooden support is sawed in such a way that the micrometer scale is slipped into position and a screw clamp pinches the two sections of the wooden support. The part of the apparatus consisting of the soil column and its follower can be lifted from the wooden supports without in any way affecting the soil sample. A different soil sample can be placed in position and measured by the same micrometer. At each measurement this movable part comes into the same position, for it is brought down firmly against the end block *B*. Since the wooden vertical supports are cut V shaped, the half-round section of brass tubing fits snugly into place.

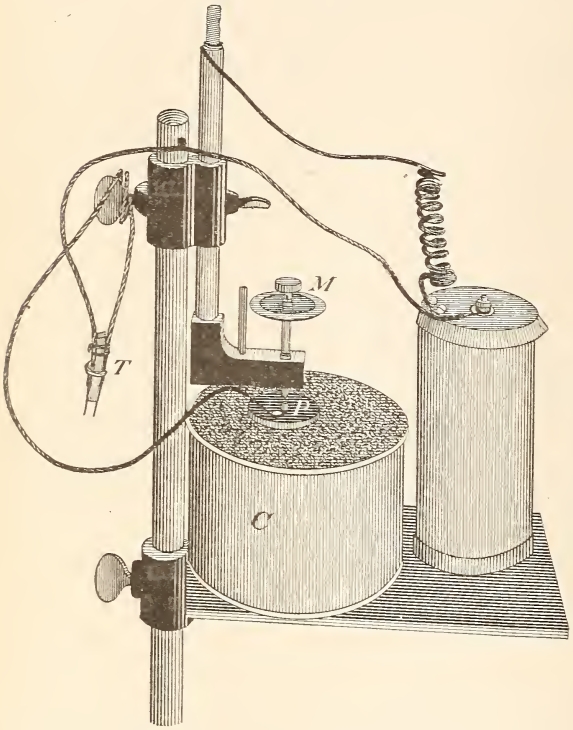

FIG. 33.—Apparatus for micrometer method of measuring changes in soil volumes.

This method has proved well suited to soils having the power to retain the form of the cylindrical soil column irrespective of the moisture content. Some soils, however, can not be successfully handled in this way, either because when wet they become incoherent and do not retain their form or because when dry they crumble. The method is not well suited for continued observations on wetting and drying of the same soil sample, because, as has been pointed out in a previous chapter, the volume changes tend to cause cracking of the soil: these cracks become points of weakness and in time cause the breaking down of the soil column.

Micrometer method.

In order to get around the difficulties just described the "micrometer method" was devised, in which the soil sample is better supported, being held in a cup. The form of apparatus is shown in

figure 33. The soil sample is contained in a cup C, which has a perforated bottom through which the soil may be wetted. This cup rests directly on the metal table of an adjustable stand, to which the micrometer screw is also attached. This method of support has a distinct advantage, since there is little possibility of the table and micrometer changing their relative positions and thus affecting the results. The variation in the height of the soil surface is measured by means of the micrometer screw M. A brass plate P with a projecting short vertical shaft rests on the surface of the soil. The micrometer point is brought just into contact with the top of the shaft. The contact is determined in the same manner as described in the preceding method. In order to obtain a good electrical contact with the plate P without disturbing its position in any way, a drop of mercury is held in a depression drilled into the surface of the brass.

This method also permits measurements being made on a number of samples, since the cup C can be removed from the table and another cup inserted in its place without displacing the micrometer. The moisture content of the soil sample corresponding to the time of measurement is determined in both this and the soil column method by directly weighing the supporting dish, the dry soil equivalent being determined when the sample is first prepared. Although the micrometer screw used in this method measures to 0.0001 centimeter, measurements were ordinarily made only to 0.001. On account of the electrical conductivity of the moist soil and since the cup rests on the metallic table it is necessary to insulate the brass plate P from the soil. This is done by fastening a hard rubber disk to the underside of the plate. The same result can, of course, be obtained by insulating the cup C from the stand. In this method the amount of surface exposed to evaporation is not so large as in the soil column method, so that the time required for a series of measurements is somewhat longer. Because of the better support of the soil column this method is applicable to almost any soil and quite independent of errors due to a defective soil column. In any future work it would be well to use larger dishes; this would tend to reduce to a minimum any errors due to adhesion between the soil and the cup. A deeper dish may profitably be used, thus giving a larger linear change, but it must be not deep enough to cause a large difference in moisture content between the lower and upper soil layers.

Cathetometer method.

The cathetometer method closely resembles the micrometer method. The soil is contained in a similar dish and the up and down movements of a point fastened to a brass disk are measured by means of a cathetometer instead of a micrometer. This method is valuable

as a check method, showing that the same results are obtained irrespective of the method used. It offers no particular advantage over the micrometer method and possesses some disadvantages. Since the cathetometer and the soil are placed several feet apart, they have no support in common, and a change of pressure on the floor may cause a variation in the level and a corresponding error in the readings obtained. Sighting the cross hairs of the cathetometer telescope on the point does not permit the same accuracy of reading as in case of the micrometer with the electric contact method. The finest graduations on the cathetometer used were 0.01 centimeter. This, added to the difficulty of reading mentioned above, made very accurate results impossible. This method might be improved by having the apparatus set up on a firm foundation, having better sighting device, larger dishes, etc., but the only advantage it can then offer over the micrometer method is that the plate on the soil surface would not be subject to any disturbing external pressure, such as might possibly be caused by the micrometer screw.

K 596